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BR53368

TR 76054

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1976

ROYAL AIRCRAFT ESTABLISHMENT
TECHNICAL REPORT 76054

**AN INVESTIGATION
OF THE INITIATION OF
HOLLOW CATHODE DISCHARGES**

by

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(14) KHE-7K-76454

ROYAL AIRCRAFT ESTABLISHMENT

(7) Technical Report 76054

Received for printing 26 April 1976

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(18) DHIC

(19) BR-53368

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(11) H1 76

(12) 48p.

SUMMARY

Extensive investigations of the starting characteristics of several hollow cathode designs have revealed that this is a random process, dependent on temperature, mercury vapour flow rate, voltage, geometry, and the availability of a low work function material. For a given cathode and fixed conditions, the voltage necessary to start a discharge falls at random within a certain range. As temperature or flow rate are increased, the maximum value and width of this voltage range both decrease until, at high values, starting is reproducible at potentials often below 20V. This behaviour appears to be strongly influenced by the site and rate of dispensation of the low work function material.

A qualitative explanation of the results at high flow rate is proposed in terms of collisional ionisation of the vapour by thermionically emitted electrons. At lower flow rates, it is necessary to include electron reflection from the keeper electrode and perhaps, at the lowest flows, a vacuum arc mechanism.

Success was achieved in initiating discharges using internal electrodes, employing either low positive voltages or much higher negative potentials. In the former case, it was difficult to transfer the internal discharge through the cathode orifice to the keeper.

Departmental Reference: Space 506

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1 INTRODUCTION

Many electric propulsion devices exist which are capable in principle of efficiently performing the station-keeping, attitude control and orbit-changing tasks necessary for obtaining the maximum benefit from an investment in earth satellites. Of these devices, the electron bombardment ion thruster using mercury propellant shows particular advantages for missions of long duration, and it is therefore the subject of extensive development programmes in several countries, including the UK.

Most of the electron bombardment thrusters being studied^{1,2,3} employ a hollow cathode⁴ as an electron source. Although the efficient operation of this component is essential if a thruster is to perform as required, most investigations of such cathodes have concentrated on parametric studies^{5,6} and life tests⁷, apart from a number of experiments at the RAE^{8,9} and in the USA^{10,11,12} in which physical processes were investigated. A major aim of the work at the RAE has been to understand as fully as possible the relevant electron emission mechanisms to allow future designs to be produced with confidence that they will prove suitable for their intended applications.

With the realisation that electric propulsion systems will probably be applied at first to the north-south station-keeping mission¹³, it has become apparent that the ability to operate a thruster without deterioration for thousands of hours is no longer sufficient. It must also be capable of rapidly starting from cold thousands of times, and it is therefore important to identify the parameters governing this process, so that problem areas can receive attention. In the case of the electron bombardment thruster, the ability to initiate the discharge on demand is largely dependent on the hollow cathode. For this reason, this aspect of hollow cathode operation has been studied in conjunction with the fundamental investigations mentioned above.

As far as is known, this is the first attempt at a systematic examination of this important factor in the operation of ion thrusters. Other workers have referred briefly to the activation of the low work function material contained within the cathode¹⁴ and to the values of voltage, temperature and mercury flow rate required to initiate a discharge^{7,15}, but no experiments have been reported in which an effort has been made to determine in detail the starting characteristics of any cathode.

In the work reported here, it was found that such characteristics are more complex than was thought initially from considerations of other gaseous breakdown phenomena. In particular, under any one set of conditions, the initiation voltage required was not reproducible, but fell within a certain range, the magnitude of which depended strongly on temperature and flow rate. In deciding upon suitable initiation parameters it is therefore necessary to compromise between these three quantities, and this will involve the design of the appropriate power supplies and control circuits. Thus the work described here has implications beyond the design of the cathode itself.

Early in the programme, alternative methods of initiating hollow cathode discharges, other than using the keeper electrode shown in Fig.1, were studied. These employed separate igniter electrodes either within the cathode body or in the plume of mercury vapour emerging from its orifice. Although successful, these methods were not pursued in detail. However, recent work in the USA^{16,17} using pulsed voltages and, in some cases, auxiliary electrodes, has suggested that a re-examination of these techniques may be desirable, because there is evidence that they may prolong cathode life and therefore increase overall thruster reliability.

2 THE HOLLOW CATHODE

The cathodes investigated were based on those originally produced for the NASA Lewis SERT II programme¹⁵, although considerable design modifications have resulted from studies in the UK of their performance and durability, both in diode test systems^{4,8} and in operating thrusters^{18,19}. As mentioned in section 1, these studies have been largely concerned with understanding the mechanisms occurring in the cathode emission process, but sufficient technological developments have also been accomplished²⁰ for there to be some confidence that they will perform adequately for the duration of currently envisaged missions.

These developments have led to the design of the cathode assembly used in the UK T4 thruster system^{1,21}. Although much improved thermally when compared with the simple cathodes tested in the work reported here, the T4 cathode is fundamentally similar to these earlier and less complex types. Thus the information gained in this study is thought to be broadly relevant to the cathode used in the thruster, although, at the time of writing, a detailed comparison remains to be made.

2.1 Cathode body and tip

Although the experiments reported here occupied a long period and utilised many cathodes, often incorporating minor design changes, the basic configuration remained unaltered. As shown in Fig.1, a typical cathode consisted of a tantalum tube into one end of which was welded a 1mm thick tungsten disc containing an axial parallel-sided orifice. On occasions, the tube and tip were made of molybdenum to simplify the fabrication of special orifice shapes. The outside diameter of the tube was usually 4mm, with a wall thickness of 0.5mm, but occasionally the dimensions were reduced to 3.2 and 0.2mm.

2.2 Cathode heater

Surrounding the tube at its closed end was a spiral heater wire encapsulated in a ceramic material. The wire was generally of 0.2mm diameter pure tungsten, but tungsten/3% rhenium was sometimes used, as were larger diameters. Two forms of winding were employed. The preferred type was bifilar, as in Fig.1, while the other consisted of a single helix, with one end spot-welded to the cathode tip or with both ends free. The free ends of the heater wire were terminated by crimping and spot welding into stainless steel tubes partially embedded in the ceramic.

In the early experiments, the ceramic was a proprietary zirconia-based compound (Aremco Ultra-Temp 516), which requires careful heat treatment. In later work, flame or plasma-sprayed alumina was used, which possesses superior properties at high temperature, does not degrade with time, and is more resistant to thermal shock. However, it reacts with tantalum at high temperatures²², necessitating the use of a barrier layer on the cathode body. The latter was normally flame-sprayed molybdenum or plasma-sprayed tungsten.

2.3 Barium source

Most hollow cathodes used in ion thrusters have contained a source of low work function material, such as barium, ostensibly to improve their thermionic emission capabilities. Although it is now thought that the effect of this material may be more complex^{4,9}, its presence is nevertheless essential if a cathode is to operate at a relatively low temperature, with a low potential in the external plasma. A common technique is to introduce a mixture of the carbonates of the alkali earth metals, chiefly BaCO_3 , into the cathode. An activation process is then necessary to produce BaO and free barium. This consists of heating gradually to about 1200°C , where the carbonates reduce to oxides. The latter then react slowly with the substrate to produce free metals.

There are essentially four methods of applying the carbonates, the first three of which were used in the work described here. They are:

- (i) coating the inner wall of the cathode body¹⁴. This is difficult to control;
- (ii) coating a thin strip of tantalum foil which is then rolled into a spiral on a mandrel before being inserted into the cathode body. This technique, which was used in the SERT II thruster¹⁵, is fairly reproducible, but is more susceptible to vibration damage;
- (iii) coating the inner or outer surface of a cylindrical metal insert with a controlled quantity of carbonate. This is reproducible, but only small quantities can be used. (The dispensation rate from the outer surface appears to be rather low at moderate temperatures, whereas a coating on the inner surface is rapidly eroded by ion bombardment from the plasma within the cathode.)
- (iv) the impregnation of a porous metal insert by suitable low work function materials^{23,24}. This technique is reproducible, is more resistant to damage caused by vibration, and is therefore preferred for flight thrusters, including the UK I4 design²¹.

Methods (ii) to (iv) are illustrated in Fig.2. In each case the insert must be in good electrical contact with the cathode body to ensure that the emission current can be drawn from the power supply, which is normally connected to the body.

2.4 Non-bariated cathode

It was reported by Bessling⁶ during the early phases of this work that it had been possible to operate a hollow cathode containing no low work function material, with no degradation of performance. The data on which this conclusion was based were obtained using a special cylindrical tantalum insert, as shown in Fig.2d, although the function of this component was not made at all clear in reports of the work. These experiments were repeated as closely as possible during the investigations reported here⁹, but, as described in section 4.5, it was not found possible to substantiate the results obtained by Bessling⁶.

2.5 Cathodes with auxiliary electrodes

The early stages of this work included a study of the use of internal and external auxiliary electrodes for discharge initiation. The methods of mounting

the internal electrodes are depicted in Fig.3. The external ones were inserted radially into the plume of mercury vapour emerging from the cathode orifice, either between the keeper and cathode or just beyond the keeper orifice. The external electrodes were tungsten or platinum wires, whereas tungsten wires or stainless steel tubes were used internally, the tips of the tubes being protected from ion bombardment damage by short niobium sections. All electrodes were externally insulated with thin-walled alumina tubing.

The tips of the internal electrodes were positioned about 2mm from the internal faces of the respective cathode tips. As shown in Fig.3, the vapour flow was passed through the tubular electrodes.

The major problem in producing the internal electrode assemblies was in making the electrical connections to them, while maintaining leak-free systems. To achieve this, each electrode was mounted on a stainless steel flange which was clamped between two boron nitride discs by bolts passing through the cathode and vaporiser flanges. Sealing was accomplished successfully by the use of knife edges and gaskets made of a proprietary asbestos based composition material. A heater was brazed to the central stainless steel flange to maintain the temperature of the complete assembly high enough to prevent internal mercury condensation.

2.6 Cathode operating procedure

As will be described in section 4, a discharge was normally initiated between a hollow cathode and a nearby keeper electrode by heating the cathode, while simultaneously passing mercury vapour through it at a suitable rate and applying a high voltage to the keeper. Once this discharge was established at a few hundred milliamps, it could be transferred to a more distant anode at a potential of 10 to 50V. Currents of many amps could then be drawn to the anode and the cathode heater could usually be turned off.

Extensive investigations have been made in diode systems of the voltage-current characteristics of discharges under a variety of conditions^{4,8,14}. It was found, in agreement with other workers, that two main discharge regimes usually exist, termed the spot and plume modes. The latter is found at low currents and flow rates and is typified by high luminosity and noise levels, while the former involves higher currents and flow rates, and produces little noise or luminosity. Although an explanation of these modes has been proposed^{4,9}, it is by no means complete.

3 THE APPARATUS

All experiments reported here were performed in diode discharge arrangements mounted in vacuum systems specially constructed to handle large quantities of mercury vapour. A common arrangement was to mount a glass cross or T-piece on an auxiliary cold trap supported by the top flange of a conventional pumping system. The glassware was either 3in or 4in internal diameter and one arm carried a flange to which was fixed Pirani and ionisation gauges. A flange on a separate arm carried an experimental diode discharge system, such as that depicted in Fig.4.

The auxiliary cold trap was provided to condense the mercury vapour emitted by the cathode/vaporiser assembly before it could enter the diffusion pump of the vacuum system. A stainless steel tray was fitted beneath this trap to collect any liquid mercury dripping off the trap when it was warmed to room temperature. With both this trap and the one incorporated into the vacuum system filled with liquid nitrogen, the background pressure in the glassware was usually in the low 10^{-6} torr region. However, the work reported here was done using several different systems, so ultimate pressures and types of contaminants may have varied; as it was not possible to employ a mass spectrometer, the composition of such contaminants is unknown.

As shown in Fig.4, the cathode under test was bolted to a flange or spacer which could be kept at an appropriate temperature by an auxiliary heater, and mercury vapour was supplied by a vaporiser²⁵. The flow rate \dot{m} was varied by adjusting the temperature of the latter, a temperature controller being provided to maintain this constant when necessary.

In most arrangements, a large ceramic disc surrounded the tip of the cathode, and the keeper electrode and anode were mounted on this. Both electrodes were made of stainless steel. Both disc and cylindrical anode geometries were employed.

The flow rate was monitored by measuring the rate of fall of the mercury meniscus in a precision bore capillary tube feeding the vaporiser. Corrections were made to allow for two sources of error. The first was due to the expansion and contraction of the mercury in the feed system caused by laboratory temperature changes - a thermometer effect. The second was due to the variation of the volume of flexible parts of the feed system owing to the change of head and therefore of pressure with the vertical movement of the mercury meniscus.

A further source of error, another thermometer effect due to the expansion and contraction of the mercury in the feed pipe following vaporiser temperature changes, was eliminated by allowing all temperatures to stabilise before taking readings. At constant laboratory temperature, this state was achieved when the rate of fall of the meniscus in the capillary tube was steady, as demonstrated by the attainment of a linear plot of meniscus height against time.

Cathode tip temperature was measured by a Pt/Pt-13%Rh thermocouple spot-welded to the edge of the cathode tip, 0.005in diameter wires being used. In the past, doubt has been expressed concerning the effect on the accuracy of this technique of conduction losses along the thermocouple wires. Consequently, an experiment was performed²³ in which the temperatures deduced from such a thermocouple were compared with those found using two other thermally shielded thermocouples and an optical pyrometer. One of the other thermocouples was in contact with the inside face of the cathode tip, with its leads inside the body, while the leads to the other were brought away from the tip between the spiral heat shield and the encapsulated heater.

Although no attempt was made to calculate temperature distributions along the leads to the thermocouple junctions, measurements at different positions along the cathode body in a subsidiary experiment showed that the temperature increased significantly with distance from the tip, at up to about $100^{\circ}\text{C}/\text{cm}$, depending on temperature range. Thus it was assumed that the temperatures of the leads of the two shielded thermocouples also increased with distance from the tip; there were, consequently, no conduction losses from these thermocouple junctions, in contrast to the one spot-welded to the edge of the tip and brought away without shielding of any kind. Despite these very different conditions, the data²³ from the three thermocouples differed by less than 5°C at 800°C , 20°C at 1000°C , and 30°C at 1200°C . Moreover, readings consistent with the thermocouples were obtained with the pyrometer, the difference between all four values being only 40°C at 1200°C . However, it should be pointed out that the reading errors associated with the pyrometer, about $\pm 25^{\circ}\text{C}$, were larger than those of the thermocouples, and corrections should also be applied to the pyrometer data to allow for the non-black body thermal emissivity of the cathode tip. These corrections would increase the values obtained, reducing the already small discrepancy between the two techniques, but their evaluation requires information concerning the total emissivity of oxidised tungsten having a ground surface finish.

It was concluded from this experiment that the simple thermocouple spot-welded to the edge of the cathode tip gave a reasonable guide to the temperature of the tip; it was certainly adequate for comparison purposes.

4 DISCHARGE INITIATION EXPERIMENTS USING THE KEEPER ELECTRODE

From general physical principles, preliminary observations and published data, it was anticipated that the keeper voltage V_k , cathode tip temperature T and flow rate \dot{m} would be the main parameters influencing the initiation of a discharge to a hollow cathode of fixed geometry. On physical grounds, there was also expected to be some dependence on a number of other factors, such as temperature distribution, tip material and surface finish, previous discharge history, and the presence of contaminants. The geometrical factors considered to be of significance included the keeper-cathode separation L , the orifice diameters of both cathode and keeper, and the shape of the insert and of the orifice.

As it was not possible to independently control and investigate all these parameters, emphasis was placed on varying V_k , T and \dot{m} , together with factors likely to influence the rate of dispensation of barium from the insert to the exterior surface of the tip. The latter included the type of insert and the shape of the cathode orifice. In addition, the diameters of the two orifices were varied over restricted ranges.

As regards a number of the parameters not specifically investigated, efforts were made to keep many of them constant throughout all experiments. For instance, the heaters employed were designed to give the same temperature distributions along all cathode bodies, possibly with the exception of the few cathodes with bodies made from molybdenum. In addition, all cathode tips were of the same material with the same surface finish, again with the exception of those devices made from molybdenum.

Although the full discharge history of each cathode tested was recorded, only those points considered relevant to the main conclusions have been included in this Report in the interests of brevity.

Two omissions from the diagnostics employed should be mentioned. The first concerns the identification of vacuum system impurities, which could have been accomplished using a mass spectrometer. This was not done owing to lack of suitable equipment and to the belief that only normal contaminants, such as air and pump oils, would be present. Later experiments, in much improved systems,

gave almost identical results to those presented in this Report, implying that such contaminants have only a marginal effect, or that they dominate completely, at least at the 10^{-6} torr level. Of course, exposure to atmospheric pressure air is another matter entirely, and is best followed by a re-conditioning process.

The second omission was of any direct method for determining the site of the active barium within the cathodes tested. Although it is possible to obtain indirect evidence of the position of such sites^{9,11}, a direct determination would require the measurement of the barium content of surface layers within operating cathodes. This represents a formidable experimental challenge. In particular, to eliminate chemical reactions which occur when such surface layers are exposed to air, a major effort would have to be mounted to operate any cathode under study within the diagnostic device, which would probably have to employ scanning electron or ion beams or X-rays to examine the various surfaces. Gaining access to internal surfaces would be even more difficult. In view of such considerations, it was felt that the results likely to be obtained would not be commensurate with the effort required, so no work was done in this area.

4.1 Initial experience with a tubular insert

The first systematic studies were conducted using a cathode having an orifice diameter d of 0.25mm and a 2mm internal diameter cylindrical tantalum insert similar to that shown in Fig.2b, but with triple carbonate mix on its inner surface. Under cold conditions, L was 1mm.

In the initial experiments, \dot{m} and T were set to particular values and V_k was gradually increased until a discharge occurred at a value V_{kb} . The keeper current I_k was then adjusted to 100mA and the discharge was allowed to continue for a fixed time of a few minutes. It was then extinguished and a new value of T was selected. By repeating this procedure, the variation of V_{kb} with T at constant \dot{m} was obtained. It was immediately found that the behaviour was extremely non-reproducible and an additional parameter, time, appeared to influence the results considerably. For example, with $\dot{m} = 0.14\text{mg/s}$ and $T = 1220^\circ\text{C}$, rapidly increasing V_k to 500V did not initiate a discharge, but one occurred after leaving the keeper at this potential for about 1min. On the next attempt, with \dot{m} and T at the same values, the discharge started with $V_{kb} = 140\text{V}$. On extinguishing this discharge and waiting 2min, a further start could not be achieved, even with 500V applied for some while. Later, a discharge was obtained with $V_{kb} = 220\text{V}$, yet immediately afterwards the application of 500V was not effective.

In general, it was found that the starting performance was influenced by the times for which the discharge was on and off, by the duration and level of any anode current, and by the rate of rise of V_k .

As it was not possible for a thorough investigation of these factors to be included in the programme under discussion, their influence was minimised by adopting a standard procedure for obtaining data.

It was found that the most important part of this procedure was that applicable to the initial start-up following any inactive period of more than about 30min, especially if the vacuum system had been turned off. After any such delay in taking data, V_k was set at 500V, \dot{m} at the value required in the subsequent experiment, and T was increased at a rate of about $200^\circ\text{C}/\text{min}$ until a discharge was obtained. This was transferred to the anode and was allowed to run at 2A for 5min, the keeper current being set at 100mA. The discharge was then turned off and the cathode was allowed to cool.

Subsequent to this initial operation, data were obtained by fixing \dot{m} and T at the desired values, then increasing V_k at a rate of about 10V/s until a discharge occurred to the keeper. This was run for about 10s at 100mA, then was extinguished. In general, this was repeated about 5 or 6 times at the given values of \dot{m} and T before selecting new values of these parameters.

More detailed studies carried out later^{26,27}, using cathodes containing rolled foil and porous tungsten dispensers, suggested that physical and chemical processes, perhaps including the surface migration of barium through the orifice and its removal by evaporation and ion bombardment, were responsible for many of the observed effects.

On adopting the standard procedure outlined above, the results became more reproducible when data were obtained in a systematic manner over short periods of time. An example is the curve A-B in Fig.5, along which T was increased steadily from 1170 to 1330°C , with V_{kb} falling regularly from 100V to the remarkably low value of 39V. However, on attempting to repeat this, the curve C-D was obtained, suggesting considerable non-reproducibility on time-scales longer than a few minutes.

On inspection of the insert of this cathode, it was found that the carbonate mix had been sputtered away by ion bombardment over an area consistent with the theory of constant current density electron emission⁹. It was thought that this might have caused the performance degradation evident in Fig.5. To avoid

this complication, a cylindrical insert having the carbonate on its outer surface (Fig.2b) was next used in an identical cathode, with $L = 1.6\text{mm}$.

Contrary to expectations, this cathode exhibited similarly unpredictable characteristics. As shown in Fig.6, at least three types of behaviour were observed on increasing T . Curve A-B represents moderate breakdown voltages for $T < 1250^\circ\text{C}$, curve C-D is at much higher voltages, with $V_{kb} > 500\text{V}$ for $T < 1170^\circ\text{C}$, whereas curve E-F exhibits extraordinarily low values of V_{kb} for $T = 1000$ to 1260°C . The data along G-H were taken with decreasing T , and occupy an intermediate position. It should be emphasised that all points in Fig.6 were taken within a few hours under almost identical conditions.

It was apparent from these and other data that, despite the obvious lack of reproducibility, a definite trend existed. This was that at low values of T , V_{kb} could be anywhere within a wide range, but, as T was increased, this range became smaller and absolute values became lower. At the highest values of T , the range became so small that reproducible data could be obtained. It was evident that a considerable amount of effort would be required to map this behaviour as a function of \dot{m} , but it was thought worthwhile to do this in order to specify more accurately thruster starting conditions.

4.2 Detailed starting characteristics with a tubular insert

An extensive investigation was carried out of the starting characteristics of a cathode with $d = 0.3\text{mm}$ and the type of tubular dispenser shown in Fig.2b. The full results for $\dot{m} \sim 0.12\text{mg/s}$ are shown in Fig.7, where it will be seen that discharge initiation was possible from below 1000°C to 1350°C at voltages well below 50V , values as low as 15V being recorded. However, to be completely sure of obtaining a discharge, the upper envelope of the experimental points had to be exceeded, implying the use of 350V at 1150°C , falling to 150V at 1200°C and 40V at 1300°C .

The above study was repeated with $\dot{m} \sim 0.62\text{mg/s}$ and 0.02mg/s ; the results are summarised by the envelope curves shown in Fig.8. The qualitative behaviour was very similar to that at the intermediate flow rate, the lowest values of V_{kb} remaining at about 15V and the envelope curves being of the same shape. However, at the higher value of \dot{m} , starting was generally easier, being possible at below 800°C , and V_{kb} falling consistently below 50V at 1200°C rather than at 1300°C . This trend was reversed at the low value of \dot{m} , with a discharge being impossible to obtain below about 1170°C , and with V_{kb} always falling below 50V only above about 1400°C .

These and other data taken at about 25 different flow rates between 0.003 and 0.9mg/s were cross-plotted to show the variation of V_{kb} with \dot{m} at fixed values of T . The form of the envelope of the data for $T = 1300^{\circ}\text{C}$ is illustrated in Fig.9. It will be seen that the variation of V_{kb} with \dot{m} along the upper curve was much less rapid than the equivalent variation of V_{kb} with T shown in Figs.7 and 8. This suggested that sensitivity to flow rate was not so great as sensitivity to temperature.

These new data gave an indication of the possible relative merits of different methods of initiating discharges to the two cathodes of a typical thruster. The information required to make assessments of this type had not previously been obtained in any ion thruster research programme, although it is needed to evaluate the affect on system mass and reliability of providing, for discharge initiation, a high keeper voltage, a high value of T , a large mass flow, or some combination of all three.

4.3 Rolled foil dispenser

In order to ascertain the effects of using a different dispenser configuration, a cathode with $d = 0.3\text{mm}$ and a rolled foil dispenser (Fig.2a) was tested as described above.

It was immediately found that discharge initiation occurred at much lower values of T with this cathode than with the earlier ones, but that the general behaviour was qualitatively similar. Full results for $\dot{m} \sim 0.1\text{mg/s}$ are presented in Fig.10; the curves containing the data are very similar to those shown in Figs.7 and 8, which are shown for comparison purposes, but are shifted to lower values of T .

It will be noted that starting was possible at below 800°C , whereas the cathode tested earlier at 0.12mg/s would not operate at below about 900°C (Fig.7). In addition, values of V_{kb} below 100V were always recorded for $T > 1150^{\circ}\text{C}$, as against 1225°C . To achieve this with the earlier cathode, it was necessary for \dot{m} to be a factor 6 higher.

The variation of V_{kb} with \dot{m} for $T = 1200^{\circ}\text{C}$ is shown in Fig.11 for two situations. Although the outer envelope curves enclose all data obtained, a more detailed analysis showed that most of the results were grouped between the lower curves (region B) in Fig.11, the only points outside these curves being those obtained after the cathode had been unused for a considerable while (region A). Under these circumstances, the points initially obtained sometimes

fell in region A in Fig.11, but later ones were invariably in region B. The latter region was extremely narrow down to 0.03mg/s, and indicated that it may be possible to accomplish discharge initiation operationally with $V_{kb} < 50V$, assuming that T can be as high as $1200^{\circ}C$ and that contamination can be avoided.

4.4 Curved orifice cathode

In order to test one aspect of the electron emission theory proposed during the course of this work⁹, several special cathodes were constructed. One, shown in Fig.12, had a curved orifice which eliminated the two sharp edges between the inner wall and the outer rim of the orifice of a normal cathode. The triple carbonate mix was, in this case, painted onto the internal tantalum wall of the cathode body.

This device exhibited extremely good starting characteristics, as shown by the curves in Fig.12. Qualitatively, the behaviour was similar to that observed before, but values of V_{kb} were very low, being under 200V even at 0.05mg/s and $800^{\circ}C$. Such ease of starting had not been observed before.

A major departure from previous experience occurred on changing \dot{m} . As is evident from Fig.12, displacement of the envelope curves to lower temperatures as \dot{m} was increased, as in Fig.8, did not occur to a noticeable extent. Instead, a marked narrowing was observed of the range of values of V_{kb} recorded at all temperatures. This caused starting to be almost completely reproducible for $T > 1000^{\circ}C$ and $\dot{m} \sim 0.17mg/s$, values of V_{kb} below 30V always being recorded. As an example of this narrowing of the characteristics, at 0.17mg/s and $800^{\circ}C$ the range of V_{kb} observed was only 23V (57 to 80V), whereas at this flow rate a comparable range was not achieved with the tubular insert until about $1300^{\circ}C$.

As well as demonstrating excellent starting characteristics, the use of this orifice shape eliminated, under some conditions, the plume to spot mode transition instability⁴, suggesting that its use in thrusters employing low discharge currents would be beneficial. However, this has so far been prevented by difficulties associated with fabricating reproducibly the required orifice profile.

4.5 Non-bariated cathode

Early in the course of this work, it was reported by Bessling⁶ that a hollow cathode containing a tantalum insert shaped as shown in Fig.2d had operated completely normally, without any low work function material. In particular, it

was claimed that starting had been readily accomplished at normal values of \dot{m} , T and V_{kb} , and that discharge voltage-current characteristics had been very similar to those obtained when barium had been employed.

In view of the importance previously attached to the provision of a low work function material^{14,15}, a cathode identical to that described by Bessling was constructed. It was found possible to operate this in the normal way, but its performance was far removed from that of other cathodes. In general, very much higher tip temperatures were required⁹ for normal operation, the difference usually being about 200°C. In addition, discharge voltages were higher and the plume mode was dominant under conditions where it was almost absent with a conventional cathode of the same geometry. Similar results have been reported recently by Zuccaro²⁸.

It was also found that starting characteristics were much inferior to those obtained with a conventional cathode having the same orifice dimensions. In fact, to obtain this comparison, a high flow rate of 0.5mg/s had to be adopted as standard to enable the non-bariated cathode to be started at temperatures within the capability of its heater.

Although the qualitative form of the characteristics resembled those described above, at a given flow rate there was a large shift to higher temperatures, as illustrated in Fig.13. In view of this displacement of about 350°C, it is difficult to explain the results reported by Bessling⁶. More recently, Zuccaro²⁸ has also reported that extremely high temperatures and voltages are required to start a non-bariated cathode. It is interesting to note, however, that at potentials of several kV his data seemed to be reproducible, in contrast to those presented here for lower voltages.

4.6 Effect of orifice diameter

During the work described here, only two cathode orifice diameters were studied, 0.15 and 0.3mm, the former size being chosen for direct comparison with the non-bariated cathode used by Bessling⁶.

The results, for $\dot{m} = 0.5$ to 0.6mg/s, are shown superimposed in Fig.14. These indicate that a change in d produced less effect than, for instance, a large change in \dot{m} for a given cathode (Fig.8). The major difference was that higher minimum values of V_{kb} were observed with $d = 0.15\text{mm}$. These tended towards 80V at 1000°C, whereas the larger orifice then gave 15V. However, above about 1000°C the upper envelope curves in the two cases were similar,

although few measurements were made at higher temperatures with the smaller orifice cathode. This result implies that, from an operational viewpoint, a change of d within the restricted range studied has only a small influence. It should be mentioned, however, that there is some evidence²³ that values of d of about 0.5mm or larger give improved starting ability.

4.7 Effect of keeper orifice diameter

To investigate the effect of keeper geometry on discharge initiation, characteristics were obtained with the dispenser arrangement of Fig.2b and keeper orifice diameters of 2 to 4mm. It was anticipated that this range would include the two extreme cases in which, (a) the flow from the cathode orifice passed completely through the keeper orifice, and (b) in which it was partially intercepted by the keeper. In a subsequent experiment designed to ensure that the latter occurred, a tungsten spike was electrically connected to the keeper and was radially inserted into the flow through the orifice. However, in no case was a significant change of starting ability observed, suggesting that variations within these limits are unimportant.

5 DISCHARGE INITIATION EXPERIMENTS USING AUXILIARY ELECTRODES

As mentioned in section 1, a number of preliminary experiments were performed using auxiliary internal electrodes to initiate discharges to hollow cathodes. As described in section 2.5 and illustrated in Fig.3, electrodes made of tungsten wire or stainless steel tube were mounted axially within the cathodes in question. It is worth noting that the wire electrodes also proved valuable for use as internal Langmuir probes⁹.

5.1 Positive applied potentials

At the time of performing these experiments it was felt that the durability of cathode heaters would be drastically improved if starting could be accomplished at reduced temperatures and power levels, and that this might later prove to be a critical aim. It was anticipated that this might be achieved using an internal electrode, owing to the higher vapour pressure within a cathode as compared with the external pressure, and to the greater efficiency of acceleration of any internally-generated electrons by a totally internal electric field. It was also thought that the best results would be obtained with the internal electrode positive with respect to the cathode, as this would make use of the electrons thermionically emitted from the cathode wall. Collisional ionisation would then be expected to produce a dense internal plasma, and electrons would be accelerated

from this through the orifice by the electric field set up by the positive keeper. Thus an external discharge would be set up.

It was found, as expected, that an internal discharge could be initiated at low voltages. As illustrated in Fig.15, these were often below the ionisation potential for values of T ranging from about 600°C to 1200°C . With $T = 1200^{\circ}\text{C}$ and $\dot{m} \sim 0.8\text{mg/s}$, a potential of only 6V was required to initiate a discharge, whereas this particular cathode, which had nearly exhausted its barium supply, required a keeper potential of about 500V for a conventional start. More significantly, with the heater power reduced to less than 25% of that required for normal starting, corresponding to $T \sim 520^{\circ}\text{C}$, the internal electrode still required only 30V, indicating very efficient use of the few electrons then available. This behaviour was reproducible, but it should be noted that such low temperatures are not necessarily an advantage, because they are not usually found in steady state operation, so the cathode has to be further heated once the discharge has been initiated.

Although the above results were very encouraging, a significant disadvantage was apparent, in addition to the problems of fabricating a durable internal electrode assembly. It was found very difficult to transfer the internal discharge to the keeper, possibly because the electric field in the cathode orifice due to the keeper was opposed by that due to the positive internal electrode. There was thus a point of zero field somewhere within the orifice. Only when \dot{m} was very high was the transfer possible, implying that a very dense plasma was needed to either shield the orifice region from the electric field due to the internal electrode, or to enhance the plasma flow through the orifice by diffusion processes. The situation became more difficult as T was reduced, offsetting the advantages of this starting technique.

5.2 Negative applied potentials

In view of the difficulty experienced in transferring internal discharges to the keeper when a positive internal electrode was used, the investigation was extended to include negative polarity. It was anticipated that this would reinforce the electric field produced by the keeper, assisting current flow through the orifice. It was recognised, however, that thermionic electrons from the cathode wall would no longer be of use in the initiation process, owing to the incorrect sign of the internal field. Consequently, it was probable that field emission from the internal electrode would be necessary, with the attendant need for high voltages.

As predicted, it was possible to strike internal discharges, but negative potentials of 200 to 800V were required, the exact values depending on T and \dot{m} . As would be expected if field emission were a dominant process, starting was possible at very low values of T , certainly well below 500°C . Instantaneous transfer of the discharge to the keeper always occurred, as predicted, if V_k was a few hundred volts. Ion bombardment heating then caused T to increase. However, as found more recently in pulse initiation studies¹⁶, a spot mode discharge could be obtained only if T was raised sufficiently after initiation, either by bombardment heating or by use of the heater, the latter partially offsetting the advantages of this mode of starting. In the absence of a spot mode discharge, anode and keeper voltages were high, causing severe sputtering damage to the face and orifice of the cathode. In addition, the high voltages necessary to initiate the internal discharge caused rapid erosion of the tip of the auxiliary electrode.

Additional support for the field emission mechanism came from attempts to initiate a discharge by this method to a cathode containing no barium. This was entirely successful, even at very low temperatures, but discharge voltages were high, causing rapid cathode orifice erosion.

6 THE DISCHARGE INITIATION MECHANISM

At the commencement of this work, it was expected that the phenomena to be studied would closely resemble those of normal high voltage gaseous breakdown, with collisional ionisation providing an important contribution. When characteristics such as those presented in Figs.7 to 9 were obtained, a considerable revision of these ideas was essential. It has been shown that an extremely complex situation exists; any realistic theory of the breakdown process must predict this. In particular, such a theory must account for the randomness of the data, the dependence on T and \dot{m} , and the influence of the orifice shape and of the barium supply process. While no comprehensive and accurate analysis has yet been produced, some degree of clarification has proved possible.

6.1 Barium supply

It is evident from an examination of the geometry of the various dispensers and cathodes investigated that barium production from the triple carbonate mix was probably most copious with the rolled foil device, because the area of the tantalum/carbonate interface in it far exceeded that in the other inserts. From a comparison of Figs.7 and 10, this spiral insert gave much easier starting than the tubular insert, but the curved orifice cathode showed an even better

performance (Fig.12). This implies that the location of the active barium may have been of greater importance than the rate of supply, it being possible that surface migration from the inner wall of the body to the outer regions of the orifice was enhanced by the elimination of the sharp edges found in the orifice of a normal cathode (Fig.1).

It should be pointed out that the vapour pressure of barium is sufficiently large at elevated temperatures²⁹ (e.g. about 1 torr at 900°C) to have ensured that barium produced from any accidental coverage of the surface of a cathode tip by carbonate mix during assembly was quickly removed by evaporation in the initial stages of each experiment. As another powerful cleansing mechanism was also active, ion bombardment of the tip, it was most improbable that any such accidental contamination caused the observed starting difference between the various cathodes tested.

It was also shown that the removal of the barium supply does not prevent discharge initiation, but renders very much higher temperatures necessary (Fig.13). Therefore, it may be concluded that the barium facilitates initiation by enhancing electron emission from the cathode tip to the keeper. This emission, which is probably thermionic, is considerably increased if the work function of the surface is reduced.

It has been shown by Newson *et al.*²⁰ that, under constant conditions, discharge initiation occurs when the prebreakdown current reaches a certain critical value. The time taken to attain this value will depend on the rate at which the required barium coverage can be achieved, which will be influenced by such relatively uncontrolled factors as vacuum system contamination, surface conditions in the orifice, and chemical reactions in the dispenser. Thus variable times are to be expected, especially over long periods of operation, if these parameters are not controlled.

The above mechanism also qualitatively explains the dependence of starting characteristics on previous discharge history²³. As mentioned above, it is fairly certain that any surface coverage of barium will be quickly removed by ion bombardment or evaporation once a discharge has been struck and, moreover, this cleansing will extend into the cathode for a distance determined by the current drawn⁹. Thus it is predicted that a low current discharge will have less of an adverse effect on the next start than will a high current one. However, such a prediction is complicated by the additional barium likely to be evolved from the dispenser during a high current discharge, owing to ion bombardment heating.

It may therefore be concluded that to understand fully the behaviour and function of the dispenser would require a major effort, involving the detailed study of the relevant physical chemistry. Starting problems over long periods of time may render such an investigation necessary, but experience¹⁹ indicates that present cathode performance may prove adequate in this respect. It should be pointed out here that the attainment of excellent starting characteristics may not be completely desirable, because it may require the use of a high rate of barium dispensation, which would adversely influence cathode durability. A compromise will almost certainly be necessary between these and other conflicting requirements.

6.2 Breakdown

Although thermionic emission from the cathode tip seems necessary for discharge initiation, a qualitative analysis of possible mechanisms indicates that the role of this emission is by no means clear under all circumstances. As pointed out below, although collisional ionisation is expected to play a major role in the initiation process, it can only do so under restricted conditions. Consequently, other mechanisms of a more obscure nature must also be invoked.

The lack of sensitivity to keeper orifice geometry indicates that the site of the discharge initiation process must be in the immediate vicinity of the cathode orifice. If it is situated in the major part of the space between the keeper and cathode, positioning a probe at keeper potential in the flow from the cathode would surely have changed the starting characteristic from that obtained with a 4mm keeper orifice. In addition, for collisional ionisation of the vapour to play a role in the initiation process under certain conditions, a reasonably high pressure is required, and this can be found only inside the orifice.

It is therefore suggested that, at the higher flow rates investigated (above 0.5mg/s), electrons emitted thermionically from the internal wall of the orifice are accelerated towards the keeper by the applied electric field, which penetrates a short distance into the orifice. The electrons cause collisional ionisation within this high pressure region, giving a rapid multiplication of number density. At the same time, the ions are accelerated to the tip, where they eject secondary electrons which further increase I_k . As V_k becomes larger, the Townsend breakdown criterion³⁰ is satisfied, and I_k suddenly rises to a high value. This model, however, implies that the ionisation free path λ_i must be considerably smaller than the orifice dimensions. This is only the case at large flow rates, when the internal pressure, p , is high^{4,31}. For example,

with $T \sim 1000^\circ\text{C}$ and $\dot{m} = 1\text{mg/s}$, it has been shown that $p \sim 100\text{ torr}$ ³¹. Taking the probability of ionisation, P_i , at 1 torr and 0°C to be its maximum value of 18 (p.104, Ref.30), and assuming that the depth of field penetration is of the same order as the orifice diameter, then $\lambda_i = 1/p_0 P_i \sim 0.08\text{mm}$, where p_0 is the pressure, reduced to 0°C , 0.3mm upstream of the edge of a 0.3mm diameter orifice. For this value of P_i , the electron energy gained per free path must be 35eV, so that for a uniform electric field and a cathode-keeper distance of 1mm, $V_{kb} \sim 440\text{V}$. For a lower energy per free path, say 20eV, $P_i = 13$, $\lambda_i \sim 0.11\text{mm}$ and $V_{kb} \sim 200\text{V}$. Realistic values of the secondary electron coefficient may be deduced under these conditions by application of the breakdown criterion.

These values of V_{kb} are close to the upper limits found experimentally under similar conditions and illustrate the extreme sensitivity to the local electric field. As this no doubt varied very strongly with position in the orifice, it provides an additional explanation for the variability of the data. This model does not, however, explain how initiation can occur at low potentials over large ranges of pressure and temperature, and cannot account at all for the results obtained at flow rates below 0.1mg/s, where internal pressures are too small for collisional ionisation to occur.

Other collisional ionisation mechanisms which may be invoked to overcome these difficulties include multi-step ionisation processes, perhaps via meta-stable levels. It is only processes of this type that can explain the occurrence of breakdown at the extremely low voltages, about 15V, observed on occasions in most of the studies reported here.

In addition, the model used successfully by Parker and Johnson^{32,33} to explain the detailed shape of the left-hand limb of the Paschen curve for mercury vapour may be applicable when mean free paths are of the order of or greater than the cathode-keeper distance. An important feature of this model is the reflection of high energy electrons from the keeper, which considerably enhances the possibility that they will cause ionisation by collision. It should be pointed out, however, that the application of this model is complex, even in one-dimensional geometry with uniform electric field and density. It would be a difficult task to obtain realistic predictions from its use in the present case, in which density and field vary strongly with position.

Despite the availability of these theories, it is doubtful whether they can be applicable to the cases of extremely low \dot{m} . For example, discharge

initiation was successfully achieved with \dot{m} as low as (.01mg/s (Fig.11), where $p \sim 1$ torr. Thus the pressure at the outer edge of the orifice must have been of the order of 0.1 torr, the reduced pressure about 2×10^{-2} torr and, assuming $P_i \sim 10$ for high electron energy, λ_i was about 5mm. Under such conditions, with $L \sim 1$ mm, it is unlikely that collisional ionisation could have been responsible for breakdown; a feasible alternative is a vacuum arc mechanism involving microprojections³⁴ on the surface of the cathode tip.

It has been shown³⁴ that microprojections, such as cones with heights up to about 25 μ m and tip radii of 10^{-5} to 10^{-7} cm, can produce field emission currents sufficient to initiate vacuum arcs. Fields of 10^7 to 10^8 V/cm can be achieved, with current densities of 10^6 to 10^9 A/cm² over very small areas. In a hollow cathode, the presence of barium and the high temperature would considerably assist such a process, drastically reducing the field necessary at the tip of a protuberance to initiate a discharge. An additional effect, which can become dominant under some conditions, is the resistive heating of the protuberance by the emission current³⁵. This can further increase the emission, and can lead to a runaway condition and to breakdown. Many other processes can occur³⁶, some involving the anode, but it is not proposed to discuss them here.

Assuming that a vacuum arc mechanism is sometimes responsible for initiating the discharge, there remains the problem of explaining the transition from a vacuum arc, relying on cathode spot emission, to the normal diffuse spot or plume mode discharges. However, this is understandable if it is remembered that a sheath will form over all surfaces in contact with the arc plasma, which will be particularly dense. Once that has occurred, the usual emission⁹ from the orifice and from within the cathode will be set up, so that less current will be drawn from the cathode spot and, in all probability, the initiating arc will be extinguished.

7 CONCLUSIONS

Although the data presented in this Report have been assembled from a number of individual tests carried out over a long period of time, they constitute a significant attempt to obtain an understanding of the processes involved in hollow cathode discharge initiation. As far as is known, no other similar studies have been reported so, although the initial aims of the work cannot be claimed to have been fully accomplished, these investigations provide the only source of systematically gathered information relevant to ion thruster cathodes. As such, this information gives a qualitative guide to the relative importance

of the many parameters involved and to the likely results of varying them. A direct, quantitative application of the data to thruster design or operation is not possible, however, because of significant differences in configuration between the laboratory cathodes tested in the work reported and the more advanced thruster components.

It has been shown that the initiation of a discharge to a hollow cathode by the standard method of applying a high voltage to the keeper electrode is a random process dependent on temperature, mercury vapour flow rate, voltage, geometry of the orifice and dispenser, and barium availability. For a given cathode and fixed flow rate and temperature, the voltage necessary to start a discharge falls randomly between two limits. Above the upper limit, a discharge will always occur, whilst below the lower limit one can never be obtained. As temperature and flow rate are increased, these limits approach each other until, at sufficiently high values, they merge and behaviour becomes reproducible. In the design of a thruster system, it is desirable to choose these parameters so that the upper limit is always exceeded.

It was found that the design of the barium dispenser was an important factor. The rolled foil device gave much easier starting than the tubular insert coated on its external surface, whilst a cathode containing no barium required extremely high temperatures for starting, typically 1300°C rather than 900°C . Results for porous tungsten dispensers have been reported elsewhere²³.

Of all the cathodes tested, that with a smoothly curved orifice profile exhibited the easiest starting, with under 200V being required down to 800°C . This was provisionally attributed to an improved supply of barium to the exterior surfaces of the tip, through a greater rate of migration along the curved wall of the orifice. It should be noted, however, that the benefits of using cathodes which start very easily due to copious barium emission will almost certainly be offset by short operational life, due to rapid barium depletion. A compromise between long life and easy starting may thus be necessary.

It was interesting to find that the geometry of the keeper orifice had no obvious effect on starting characteristics. This supported the suggestion that the site of the initiation process was close to or within the orifice, where only major external changes, such as to the cathode-keeper distance, could alter the electric field appreciably.

These studies strongly indicated that thermionic emission, assisted by the availability of a low work function material, is essential to the discharge initiation process at the voltage levels investigated. However, it is far less certain how this emission is instrumental in causing a fully developed discharge.

At flow rates above about 0.5mg/s, the vapour pressure, voltages and dimensions were consistent with a mechanism involving collisional ionisation, as in conventional gas discharge processes. An exception must be made in the case of the very low voltage breakdown often observed, but this can be explained by multi-step ionisation, possibly involving metastable energy levels.

At low flow rates, electron mean free paths are so long that collisional effects can be discounted, unless electron reflection from the keeper is included in the model. Even this will almost certainly be inadequate at the lowest flow rates, especially in explaining the discharges initiated at low voltages. It is therefore postulated that a vacuum arc initiation process may then be responsible, perhaps involving field-enhanced thermionic emission from cathode micro-protuberances.

Success was achieved in starting cathode discharges using internal electrodes, despite the complexities encountered in fabricating and sealing the cathode assemblies used. It was very easy to initiate internal discharges employing positive polarities, under 10V usually being required. Transfer to the keeper was difficult, however, possibly due to the opposing electric fields produced by the two electrodes. These fields reinforced each other with negative polarity, so transfer was then very rapid. However, thermionic electrons from the cathode wall were no longer accelerated to the internal electrode, so high voltages were necessary for starting, presumably because field emission was then required. It was concluded that definite advantages could be gained by using the internal electrode technique, but that the difficulties associated with fabrication, electrode wear, and discharge transfer were too great for the method to be considered for operational use.

Although these internal electrodes were shown, on balance, to have disadvantages outweighing their advantages, it should be noted that the use of external electrodes may prove desirable. It has been shown elsewhere^{16,17} that such electrodes allow discharge initiation to occur at low cathode temperatures, if short voltage pulses of several kV amplitude are applied to them. This type of system has also been shown to be very durable, and it could offer improved cathode lifetime and reliability, through a reduction in barium dispensation during the starting transient and by decreasing the thermal stress on the heater.

SYMBOLS

| | |
|-------------|---|
| d | cathode orifice diameter |
| I_k | keeper current |
| L | keeper-cathode separation |
| \dot{m} | mercury vapour flow rate |
| p | cathode internal pressure |
| P_i | probability of ionisation at 1 torr and 0°C |
| P_0 | pressure reduced to 0°C in cathode orifice, distance d upstream from outer edge |
| T | cathode tip temperature |
| V_k | keeper voltage |
| V_{kb} | value of V_k giving discharge initiation |
| λ_i | mean free path for ionisation |

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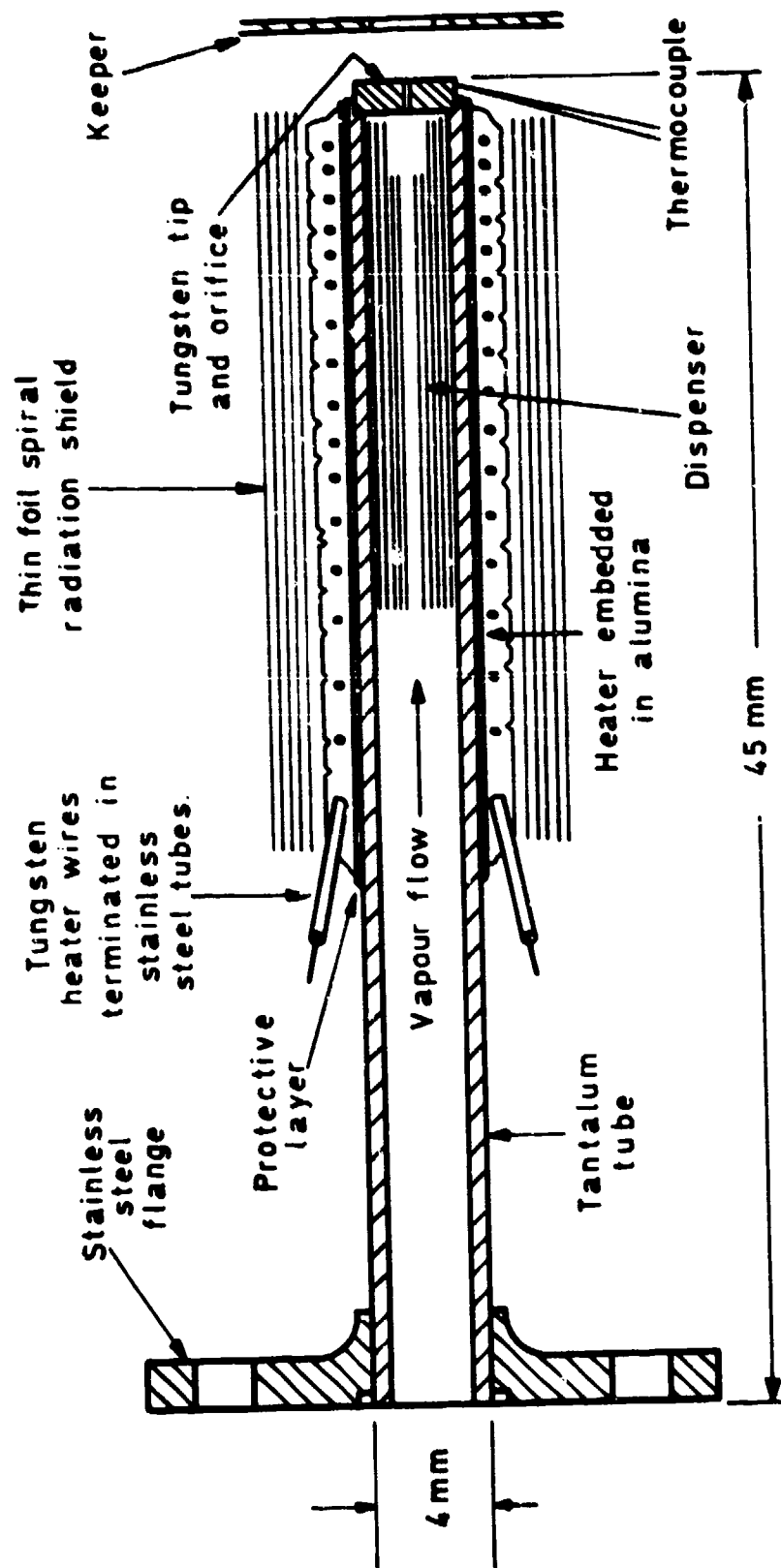


Fig.1 Section through a typical hollow cathode.

Fig.2 a-d

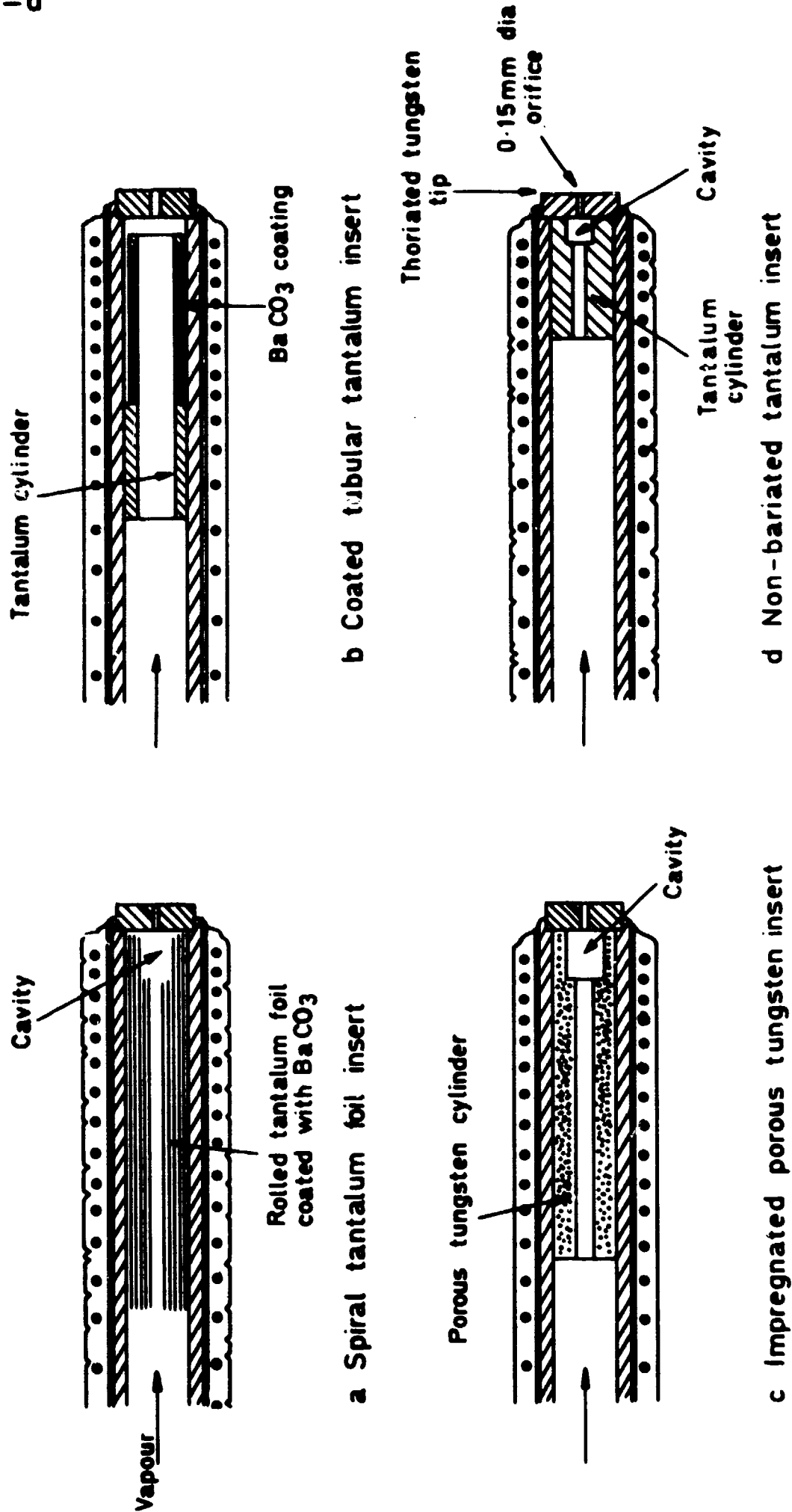
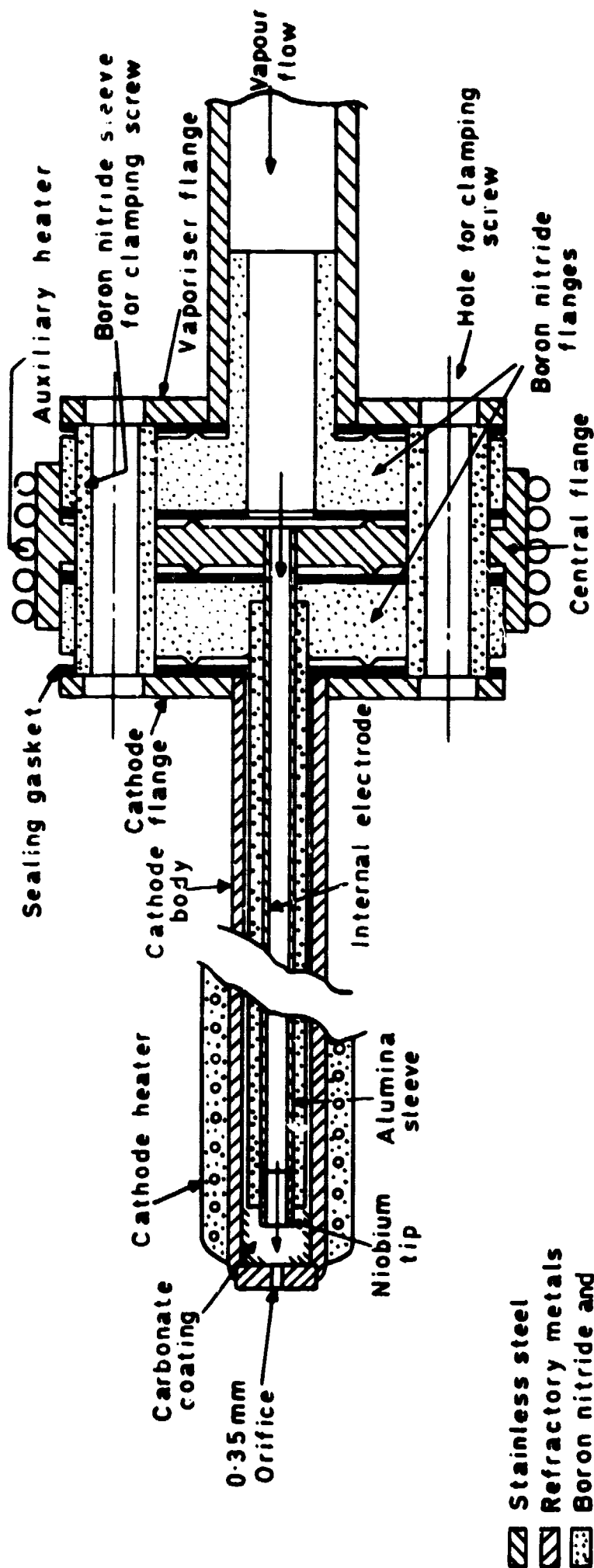
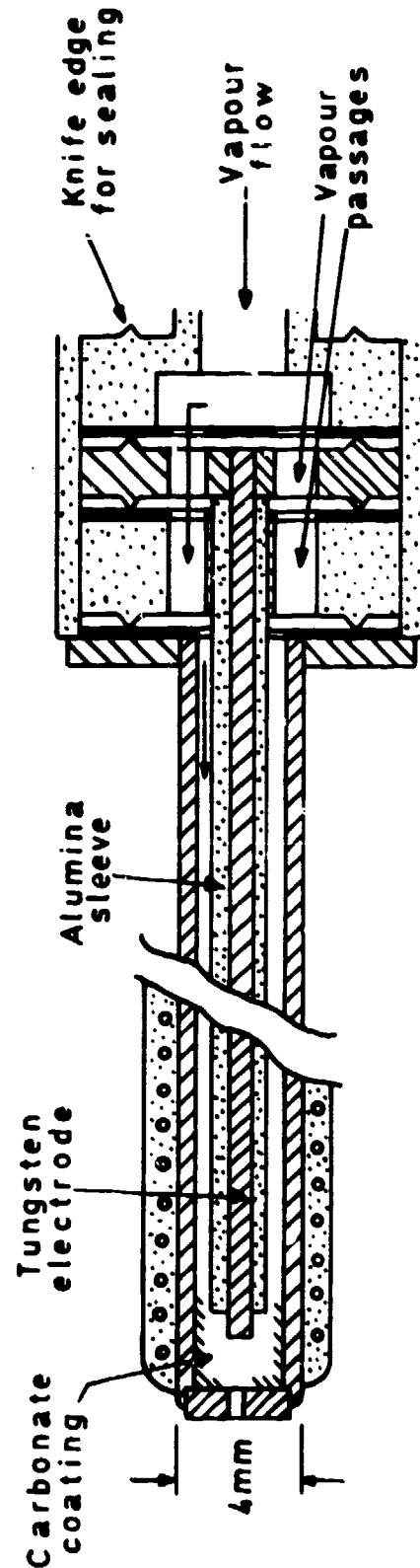


Fig.2a-d Barium dispenser configurations

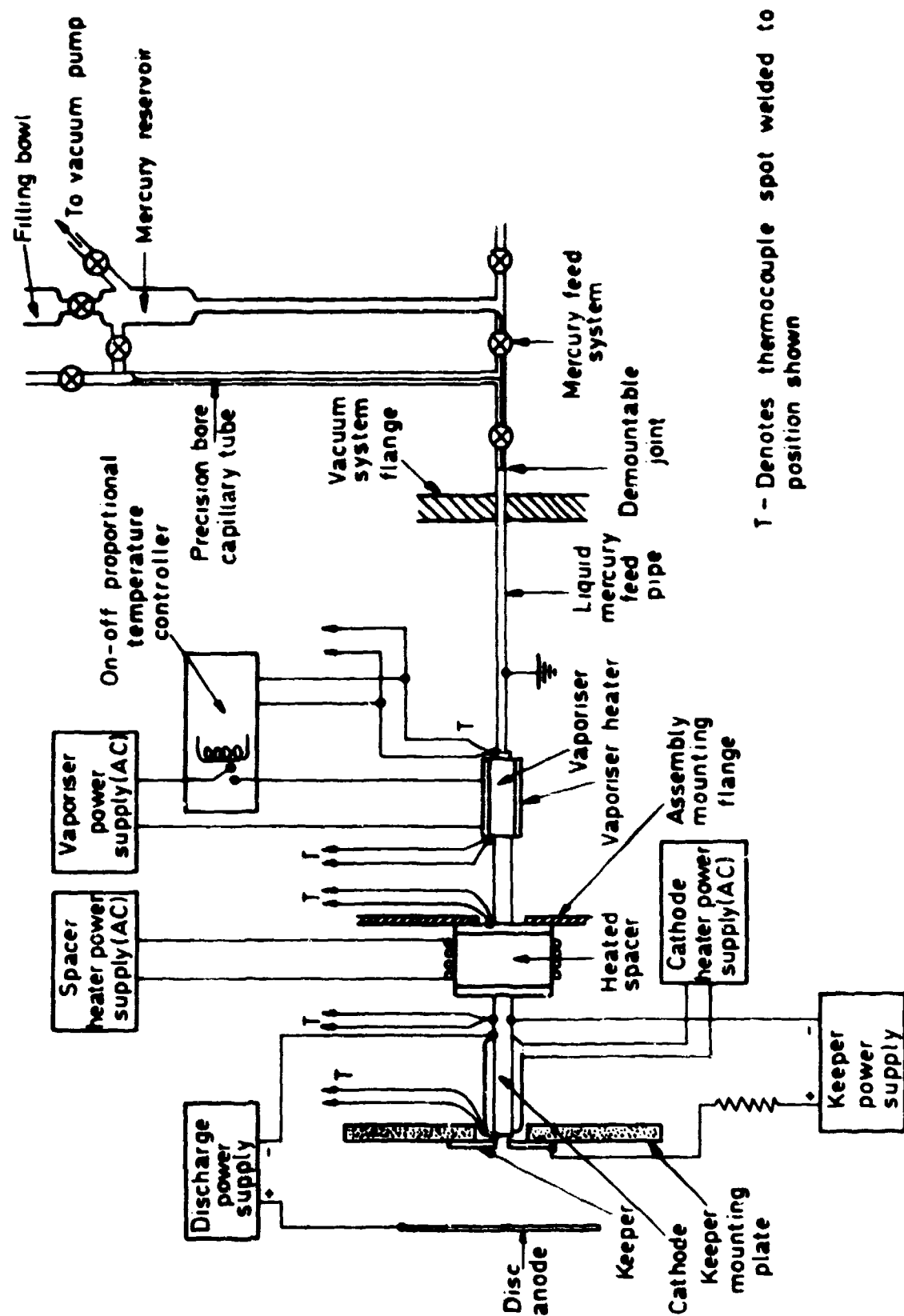


a Section showing internal tubular electrode.



b Part section showing wire electrode assembly with internal electrodes.

Fig.4



T - Denotes thermocouple spot welded to position shown

Fig.4 Schematic of typical diode system

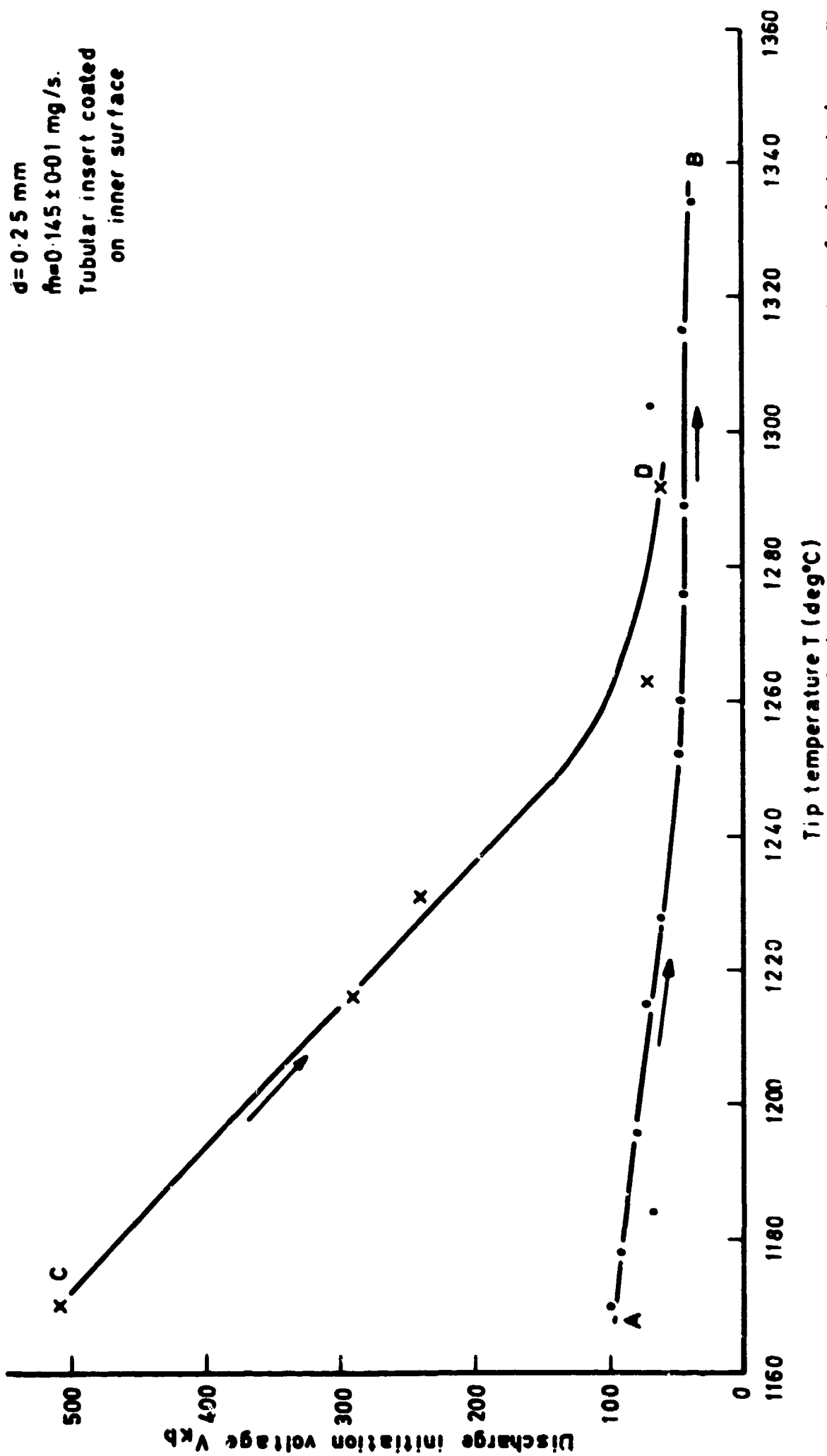


Fig. 5 Breakdown voltage as a function of tip temperature; two sets of data taken under similar conditions.

Fig.6

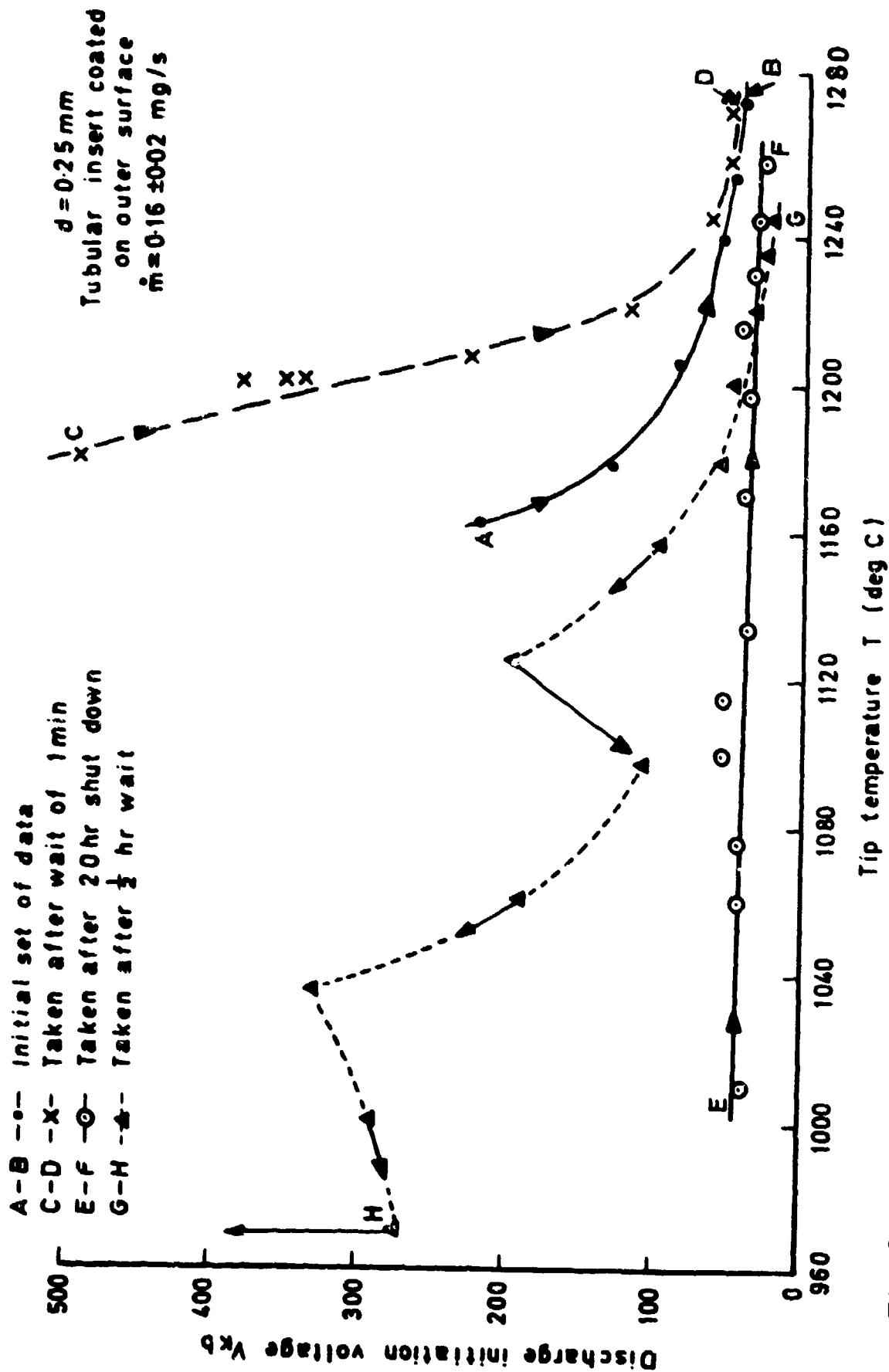


Fig. 6 Breakdown voltage as a function of tip temperature; 4 sets of data taken under closely similar conditions.

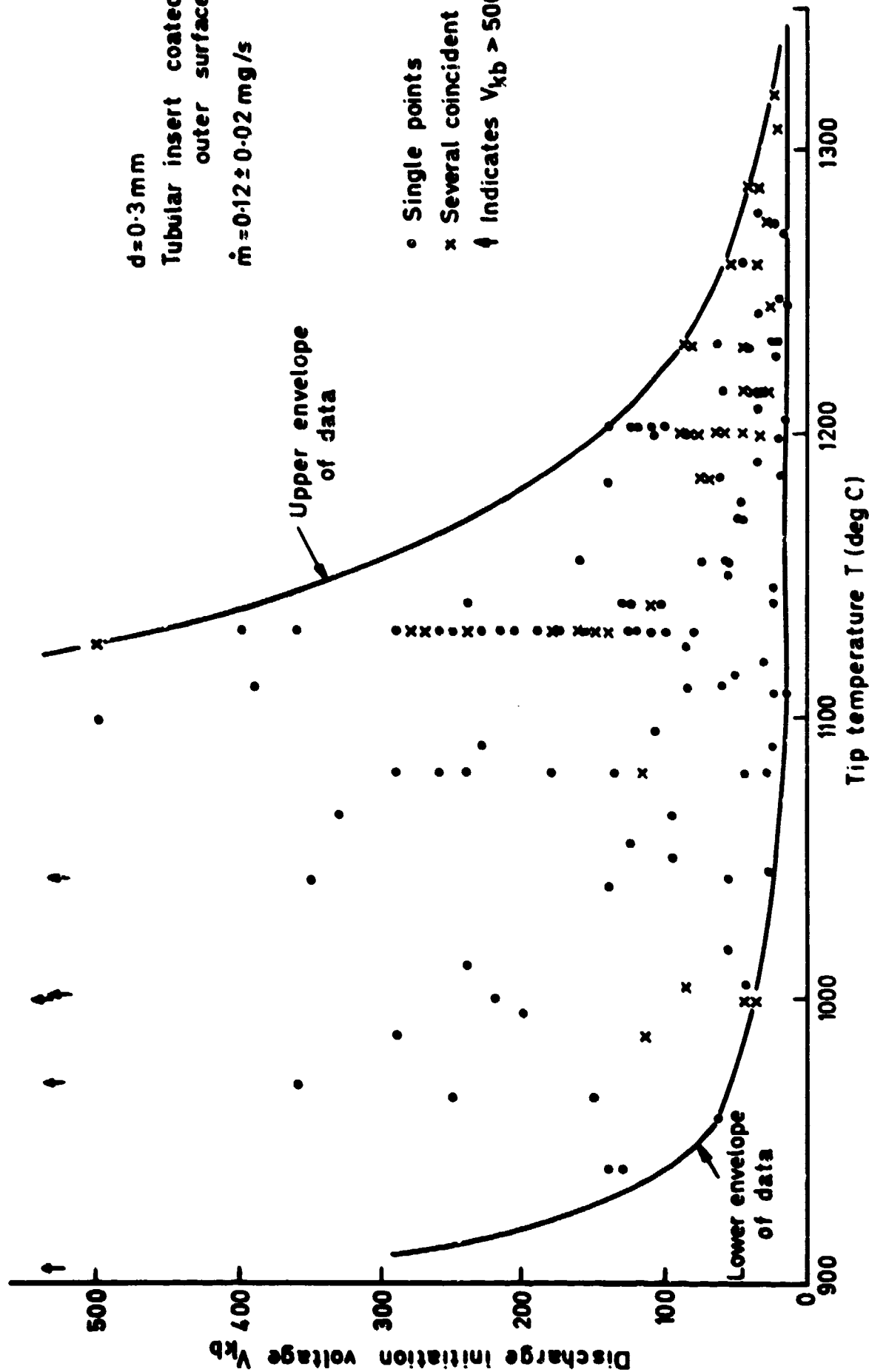


Fig. 7 Discharge initiation data for cathode with tubular insert and $\dot{m} = 0.12 \text{ mg/s}$

Fig.8

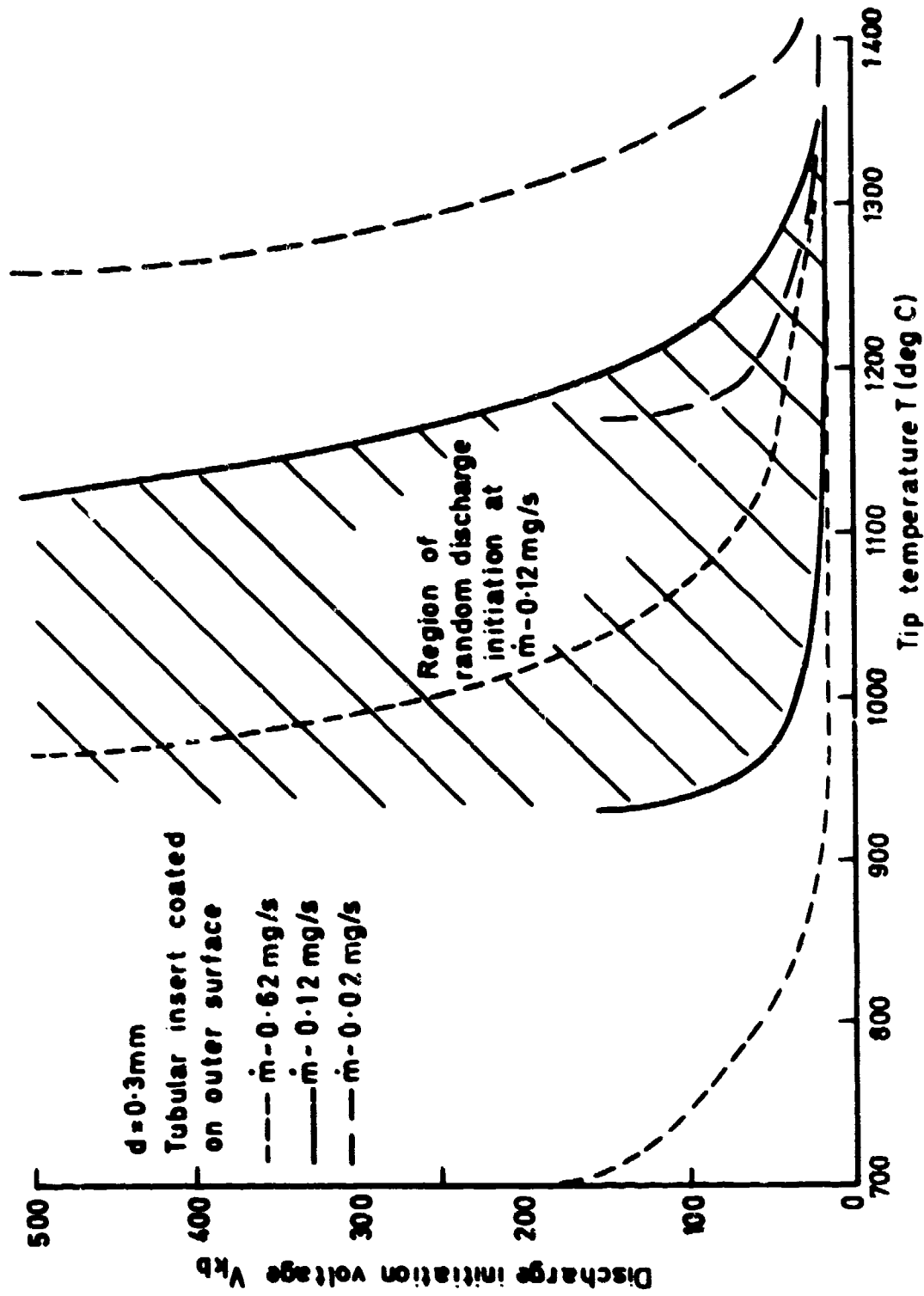


Fig.8 Envelopes of discharge initiation data as functions of tip temperature, for 3 flow rates

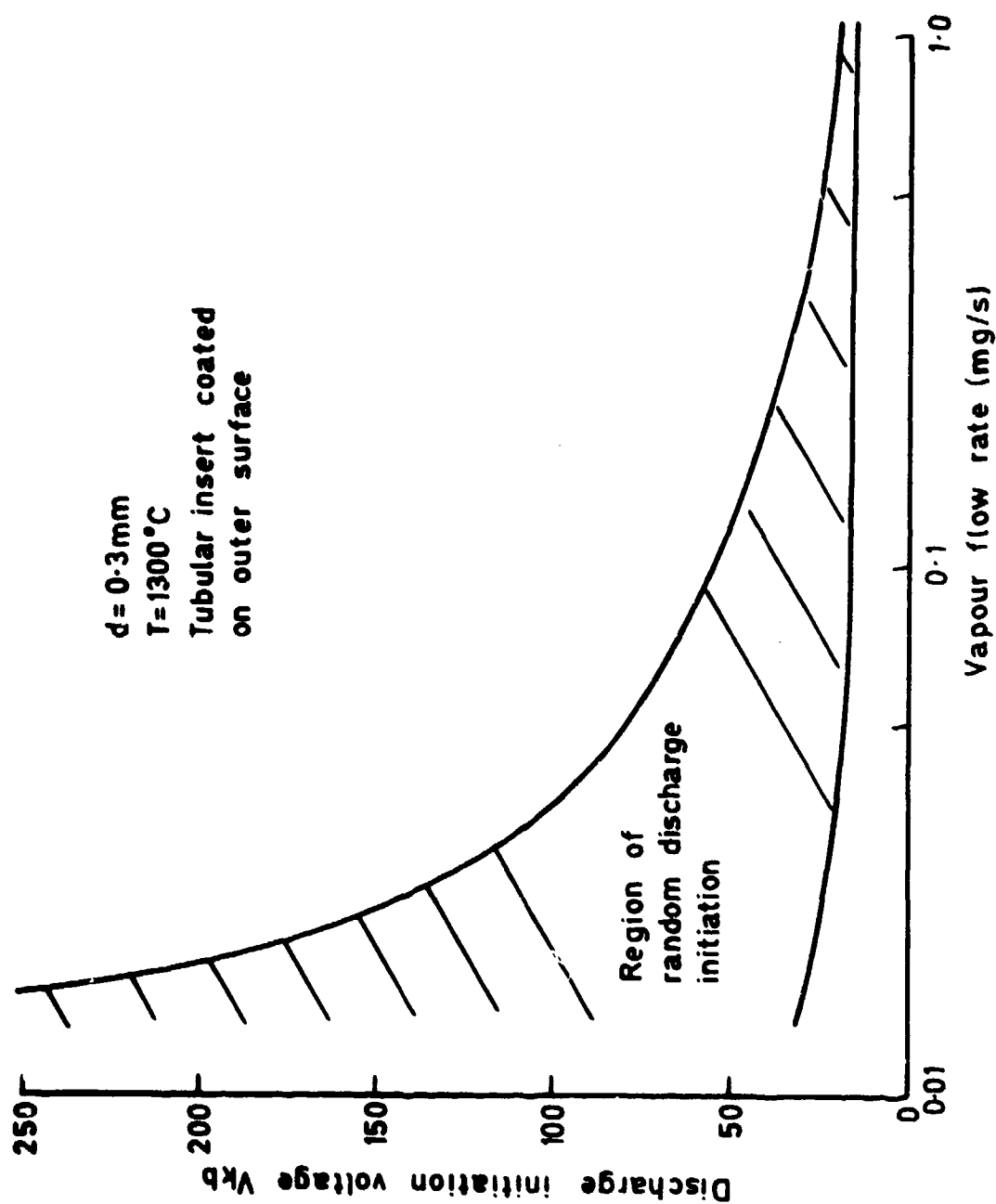


Fig.9 Envelope of discharge initiation data as function of vapour flow rate

Fig.10

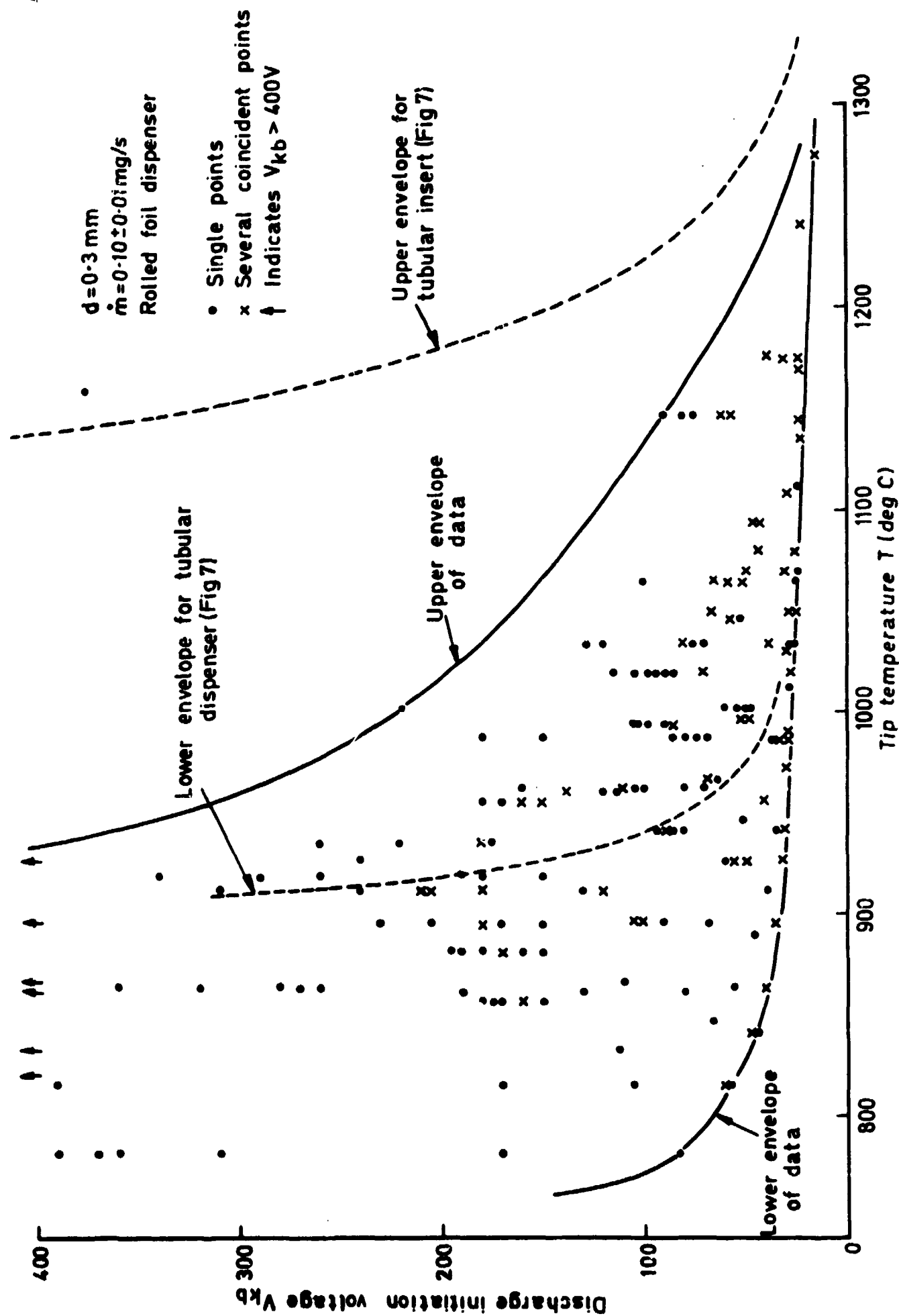


Fig.10 Discharge initiation data for cathode with rolled foil dispenser and $\dot{m} \sim 0.10 \text{ mg/s}$

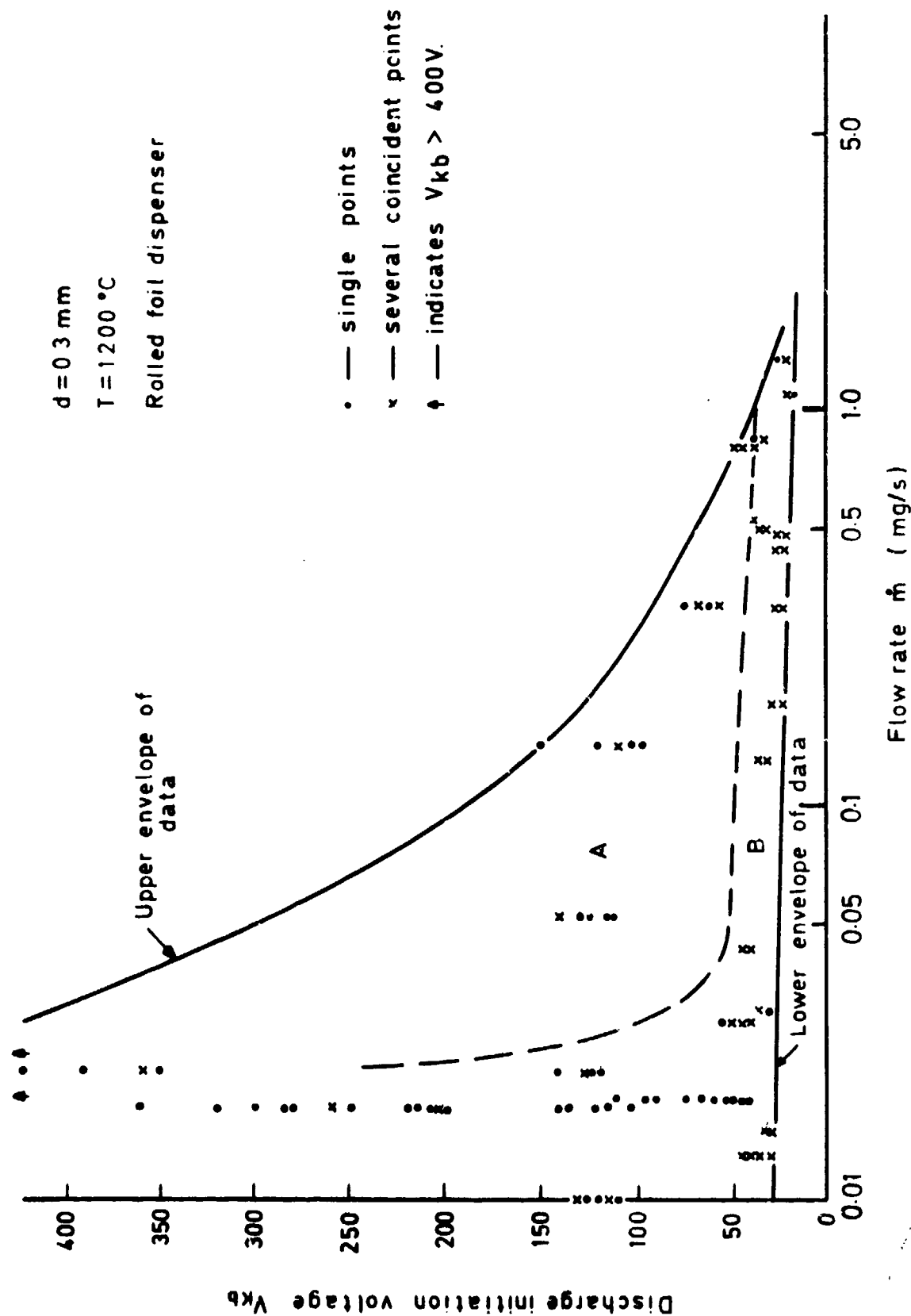


Fig. 11 Discharge initiation data variation with flow rate, for a cathode with a rolled foil dispenser.

Fig.12

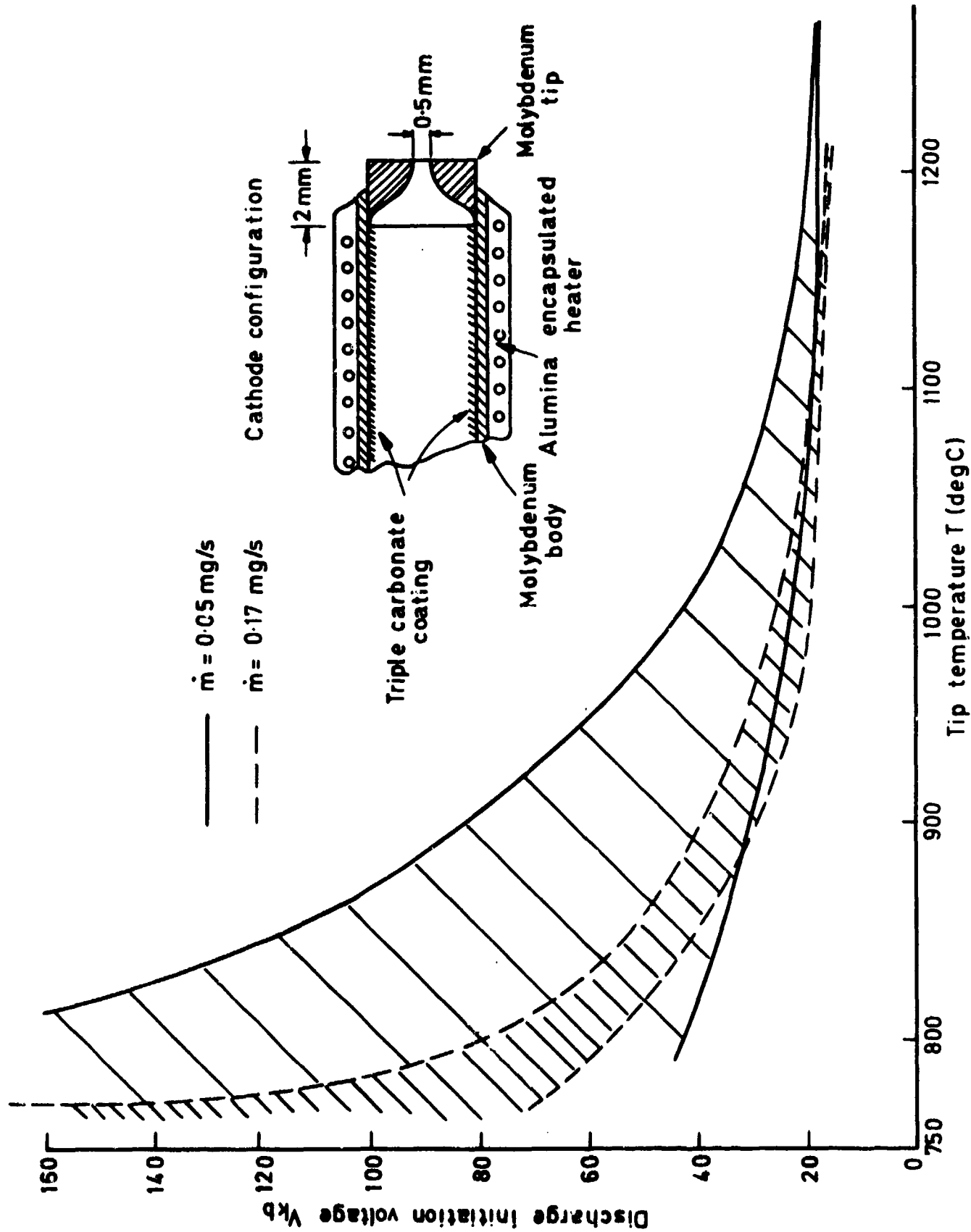


Fig.12 Discharge initiation characteristics of curved orifice cathode

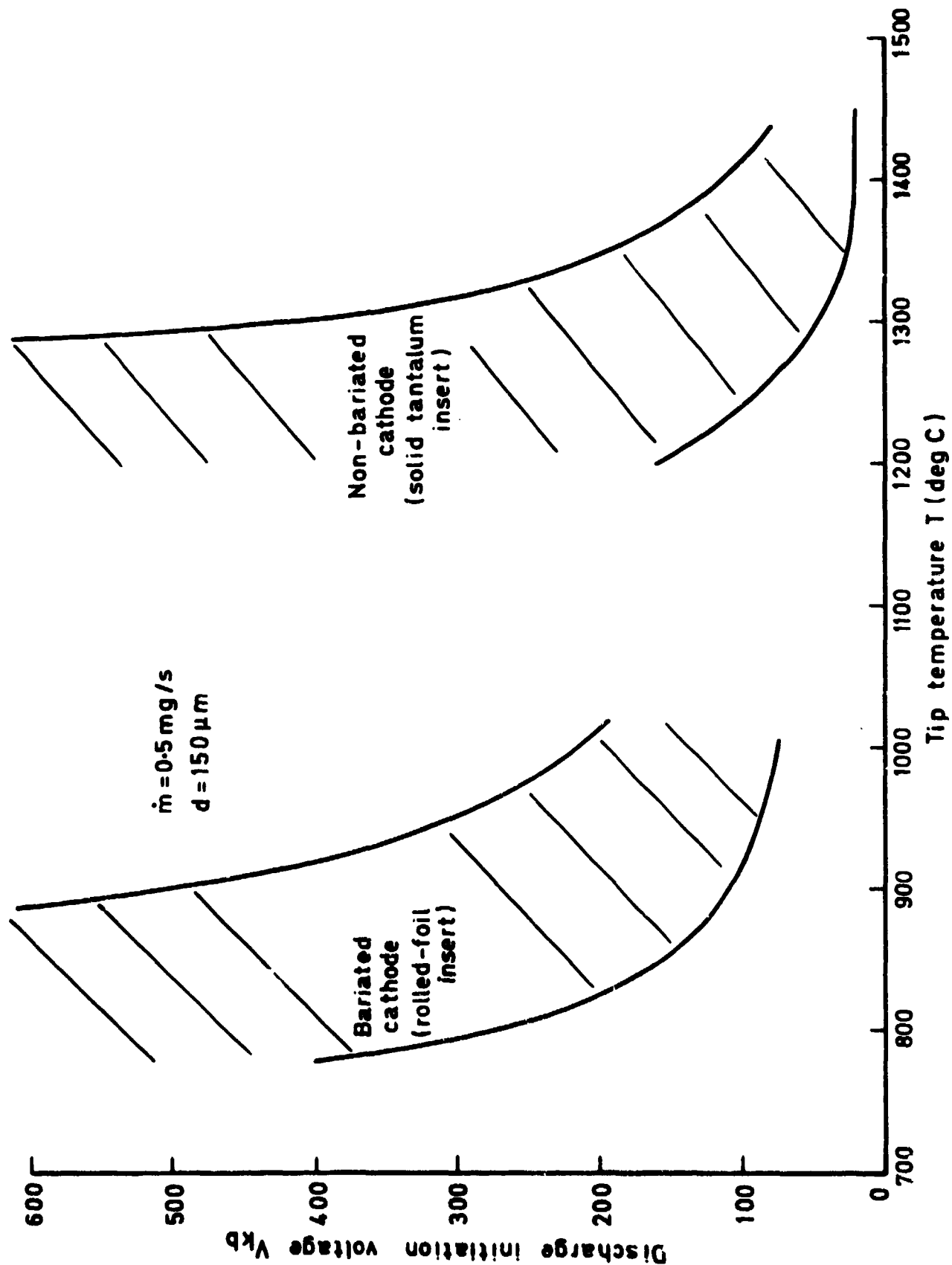


Fig. 13

Fig.13 Comparison of starting characteristics with and without barium

Fig.14

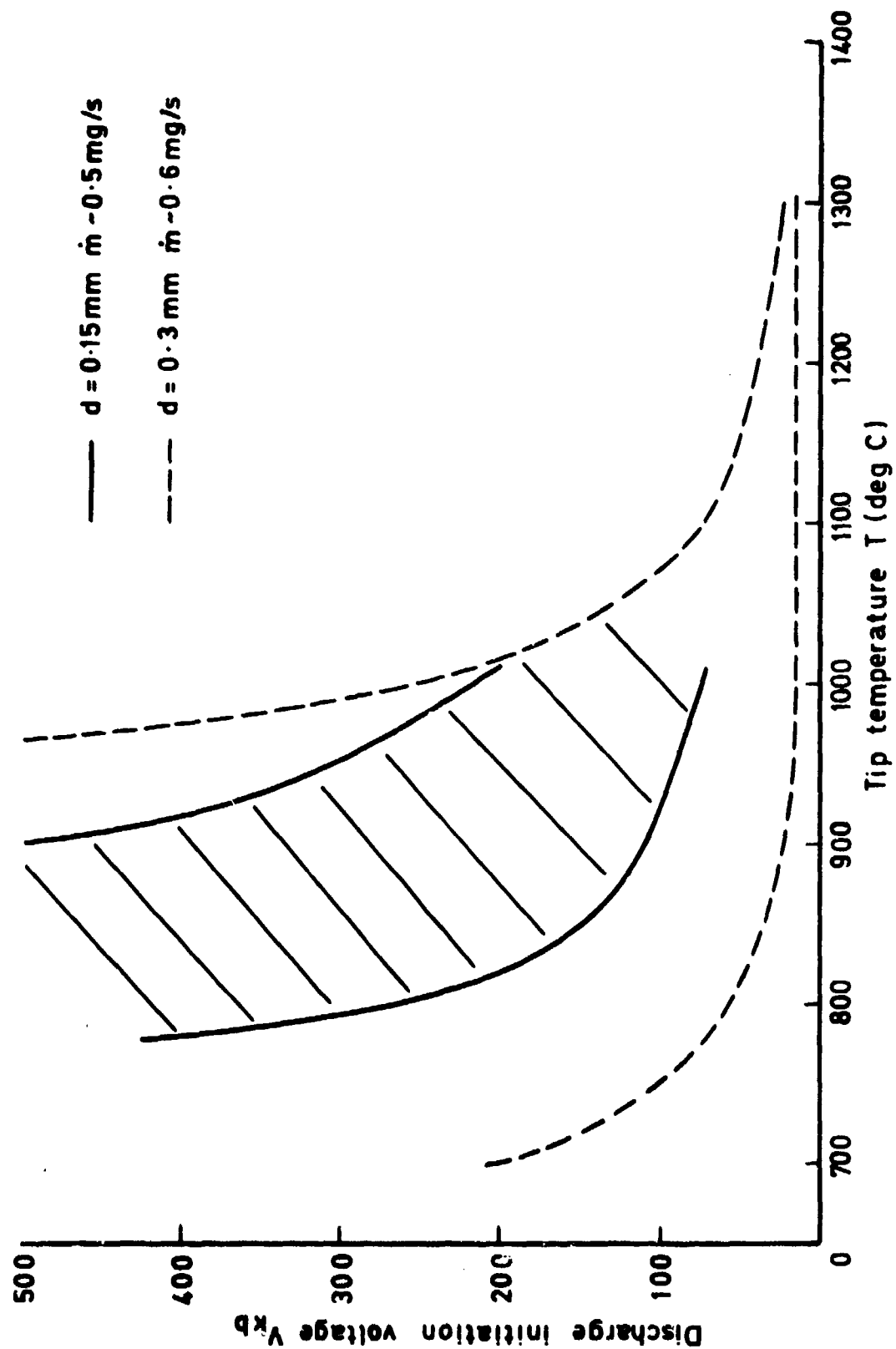


Fig.14 Comparison of starting characteristics of cathodes
with different orifice diameters

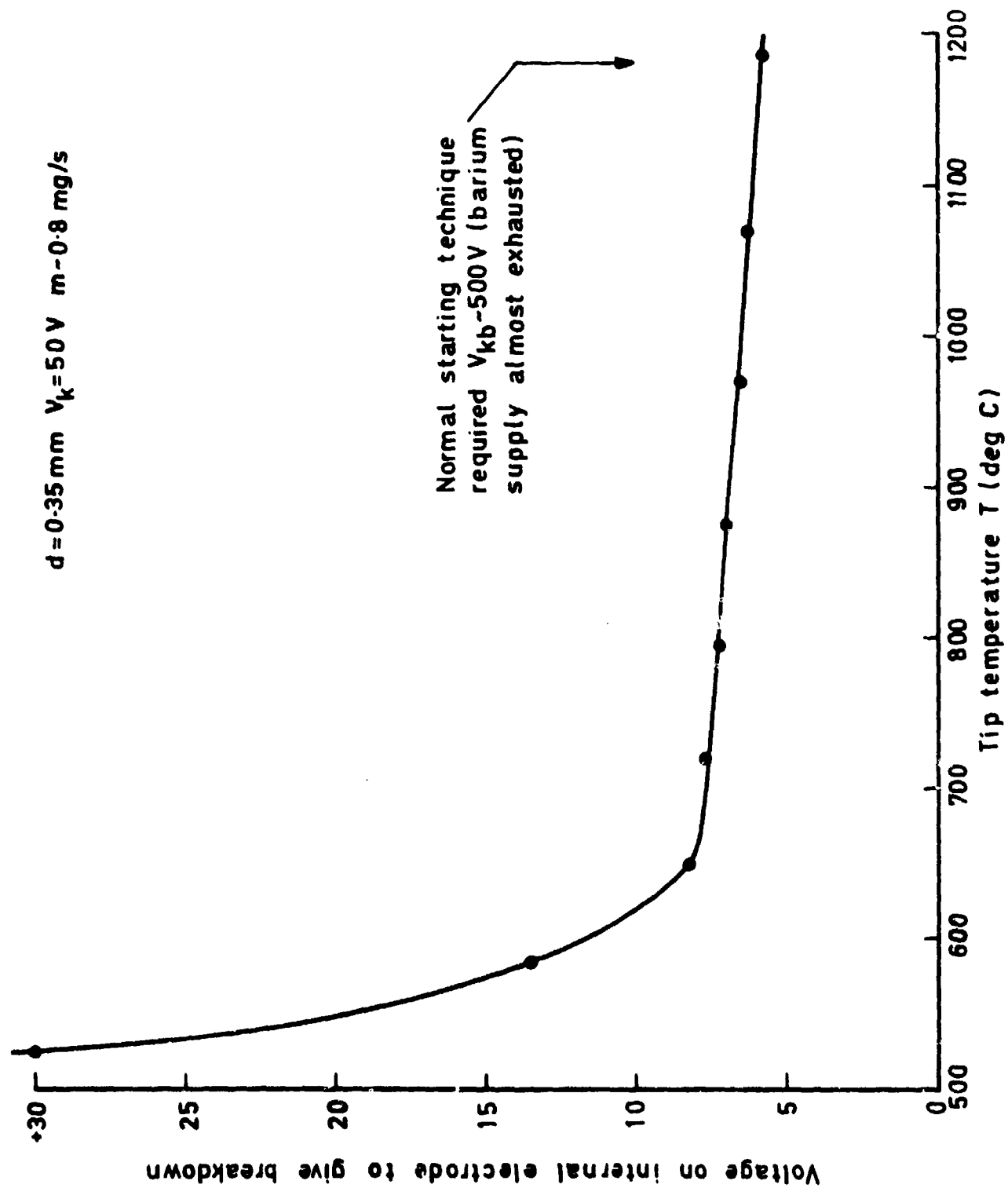


Fig.15

Fig.15 Internal electrode discharge initiation characteristics

REPORT DOCUMENTATION PAGE

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| | | | | | |
|---|---|--|--|-------------|-------------|
| 1. DRIC Reference (to be added by DRIC) | 2. Originator's Reference RAE TR 76054 | 3. Agency Reference N/A | 4. Report Security Classification/Marking UNLIMITED | | |
| 5. DRIC Code for Originator 850100 | | 6. Originator (Corporate Author) Name and Location Royal Aircraft Establishment, Farnborough, Hants, UK | | | |
| 5a. Sponsoring Agency's Code N/A | | 6a. Sponsoring Agency (Contract Authority) Name and Location N/A | | | |
| 7. Title An investigation of the initiation of hollow cathode discharges | | | | | |
| 7a. (For Translations) Title in Foreign Language | | | | | |
| 7b. (For Conference Papers) Title, Place and Date of Conference | | | | | |
| 8. Author 1. Surname, Initials Fearn, D.G. | 9a. Author 2 Cox, Angela S. | 9b. Authors 3, 4 Moffitt, D.R. | 10. Date April 1976 | Pages 45 | Refs. 36 |
| 11. Contract Number N/A | 12. Period N/A | 13. Project | 14. Other Reference Nos. Space 506 | | |
| 15. Distribution statement (a) Controlled by - DRASA MOD(PE) ASA 4 (b) Special limitations (if any) - | | | | | |
| 16. Descriptors (Keywords) (Descriptors marked * are selected from TEST) Electric propulsion*. Ion engines*. Cathodes*. Ion propulsion*. | | | | | |
| 17. Abstract <p>Extensive investigations of the starting characteristics of several hollow cathode designs have revealed that this is a random process, dependant on temperature, mercury vapour flow rate, voltage, geometry, and the availability of a low work function material. For a given cathode and fixed conditions, the voltage necessary to start a discharge falls at random within a certain range. As temperature or flow rate are increased, the maximum value and width of this voltage range both decrease until, at high values, starting is reproducible at potentials often below 20V. This behaviour appears to be strongly influenced by the site and rate of dispensation of the low work function material.</p> <p>A qualitative explanation of the results at high flow rate is proposed in terms of collisional ionisation of the vapour by thermionically emitted electrons. At lower flow rates, it is necessary to include electron reflection from the keeper electrode and perhaps, at the lowest flows, a vacuum arc mechanism.</p> <p>Success was achieved in initiating discharges using internal electrodes, employing either low positive voltages or much higher negative potentials. In the former case, it was difficult to transfer the internal discharge through the cathode orifice to the keeper.</p> | | | | | |